Effect of exchange rate return on volatility spill over across trading regions

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Abstract

This paper examines the effect of exchange rate return on volatility spill over in Euro-US dollar and US dollar-Yen currency pairs across five trading regions: Asia, Asia-Europe overlap, Europe, Europe-America overlap and America identified on the basis of quoting patterns. Three exchange rate return regimes are defined with various percentile cut-offs of the returns as threshold parameters. We hypothesise that return regime induced realised volatility proxy the interaction between information asymmetry (appreciation and depreciation of exchange rate) and trader heterogeneity (differential treatment of asymmetric information). In an autoregressive five-equation system we find evidence in intra-day data that currency depreciation has greater influence on volatility spill over than appreciation. Evidence of this is uncovered in the US dollar-Yen currency pair when depreciation/appreciation is strong and in the trading regions created with overlapping operational time.

Key words: Exchange rate, volatility spill over, high-frequency data

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1. Introduction

In foreign exchange markets currencies get converted to other currencies to facilitate international trade and investment. The daily turnover in foreign exchange markets is clearly the largest compared to that in financial markets where other instruments are traded. A distinguishing feature of foreign exchange markets from the other financial markets is that foreign exchange markets operate continuously throughout the day except weekends. Because of sequential trading across foreign exchange markets, information from the markets that have operated prior to the other markets may get passed on almost instantly. Therefore, in foreign exchange markets new information potentially gets absorbed very quickly.

Engle *et al.* (1990) investigate information spill over across foreign exchange markets with respect to volatility in the exchange rate returns. They formulate a model to examine exchange rate volatility linkages across different markets so that the source of volatility may be identified. Engle *et al.* (1990) investigate two hypotheses: heat waves and meteor showers. The heat-wave hypothesis stipulates that volatility of the exchange rate returns in a given market is influenced only by the past volatility of the exchange rate returns in the same market. Under the meteor-shower hypothesis the volatility of the exchange rate returns in a given market is assumed to be influenced by the spill over of volatility from the other markets.[1] Engle *et al.* (1990) test these two hypotheses in New York and Tokyo foreign exchange markets. In terms of operation the Tokyo foreign exchange market follows the New York foreign exchange market. So their research questions are (i) whether the volatility in the Tokyo foreign exchange market is predictable from news in the Tokyo foreign exchange market only and (ii) whether news in the New York market can predict exchange rate volatility in the Tokyo foreign exchange market. Engle *et al.* (1990) report evidence to suggest volatility clustering of meteor shower type as opposed to the heat wave type.

[1] The notion behind these stipulations is volatility clustering where large changes in volatility tend to be followed by large changes in the same.

Melvin and Melvin (2003) highlight that investigating volatility transmission with daily opening and closing price of foreign exchange markets as in Engle *et al.* (1990) is problematic because one morning and one afternoon observation may not really reflect the level of trading activity in the trading centre.[2] In high frequency data, Dacorogna *et al*. (1993) and Andersen and Bollerslev (1997) observe that intra-daily seasonality in foreign exchange volatility is associated with trading zones spread across geographically. Following this lead, Melvin and Melvin (2003) examine volatility spill over in trading regions identified through high frequency quote activity. They demarcate opening and closing times of five trading regions (Asia, Asia-Europe overlap, Europe, Europe-America overlap and America) on the time line spanning 24 hours to match with clusters of high frequency quote activity and treat the regions as sequentially operating markets. They report that even though there is statistical evidence of own region and inter-regional volatility spill over in Deutsche mark-US dollar and Yen-US dollar exchange rate returns, in terms of economic significance heat waves are more important than meteor showers. Cai *et al*. (2008) investigate exchange rate returns and direction of exchange rate returns separately allowing for its dependence on its past value and the other regions' past values and report that informational linkages across five trading regions (Asia Pacific, Asia-Europe overlap, Europe, Europe-America overlap and America) is weak. Hence they argue that the lack of return spill over and direction of return spill over suggests that foreign exchange markets are efficient in processing new information.[3] Cai *et al*. (2008) measure the direction of return by using an indicator variable taking the value +1 (-1) when the currency is stronger (weaker) and 0 when the exchange rate does not change.

In this study, adopting a modelling framework similar to Melvin and Melvin (2003), we investigate whether volatility of exchange rate returns in a given region is associated with the level of exchange rate return and the volatility of exchange rate returns in the other regions. The aim is to investigate (i) whether volatility spill over is more pronounced from certain regions than others and

[2] Examples of studies that investigate volatility spill over in foreign exchange markets at daily frequency are Nikkinen *et al*. (2005) and Inagaki (2007) and at weekly frequency is Ng (2000).

[3] Cai et al. (2008) consider return volatility, trading activity and order flow also as information proxies. In an investigation of euro-dollar and dollar-yen currency pairs they report statistical evidence of spillovers across trading regions thereby supporting the meteor shower effect.

(ii) whether volatility spill over is influenced by the level of exchange rate return. The difference between ours and Cai *et al*. (2008) study is that instead of treating exchange rate return and volatility of exchange rate return as independent proxies of information, we model return and volatility together. This is done by first creating three indicator variables that classifies a given trading day as a day of high return, neutral return or low return depending on the magnitude of exchange rate return. The thresholds used in demarcating the levels in the returns are the 70th and 30th percentiles of the normalised return series.[4] Then to induce the level of exchange rate return on volatility, we multiply volatility by the relevant indicator variable. We hypothesise that previous period volatility may have an asymmetric effect on the volatility of a subsequent period depending on the level of the exchange rate return in the previous period. We investigate this issue in the five trading regions: Asia (*AS*), Asia-Europe overlap (*AE*), Europe (*EU*), Europe-America overlap (*EA*) and America (*AM*) that has been identified in Melvin and Melvin (2003) on the basis of quoting patterns.

In a sample of intra-day exchange rate returns of currency pairs: US dollar-Yen and Euro-US dollar, we find strong evidence to support the heat wave hypothesis and that the next most pronounced spill over is from the nearest region. We dub the spill over effect from the nearest region the *nearest neighbour syndrome*. In the sample period August 2008 to July 2009 and in both currency pairs we find strong evidence to support the heat-wave hypothesis and the nearest neighbour syndrome. Therefore, to investigate the effect of exchange rate return on volatility spill over we focus on the own region and the nearest neighbour region.[5] For the currency pair US dollar-Yen, we find that volatility spill over from the nearest neighbour region is associated with level of exchange rate return. Moreover, depreciation of US dollar against the Yen tends influence volatility spill over from the nearest neighbour region more than when the US dollar appreciates against the Yen. The asymmetry

[4] We consider two other pairs of thresholds as a robustness check in section 6.1.

[5] We shall see later in section 2 that the number of parameters that will be estimated under this specification is forty-six. The effect of exchange rate return on volatility spill over across all regions is discussed in section 6.3. The number of parameters estimated there is seventy-six.

of spill over is stronger in the regions created with overlapping trading hours. In our case they are *AE* and *EA*.[6]

Overlap trading regions are generally associated with strong incidence of volatility spill over and high level of trading activity. Two factors that may cause volatility spill over are information asymmetry and trader heterogeneity in information processing. In foreign exchange markets private information is important as informed and uninformed traders may take different positions thereby creating a ripple effect of trades (Ito *et al*., 1998). Even if all traders receive information at the same time it is possible that they may interpret or use the information differently. In that case the reaction to information may be sequential thereby causing yet another ripple effect of trades. Rippling effect of trades may generate volatility that is autocorrelated across trading regions. In overlap trading regions it is easy for traders to pass positions and therefore it is plausible that volatility spill over from such regions are more pronounced compared to the other regions (Melvin and Melvin, 2003). Furthermore, overlap trading regions are associated with clusters of high frequency quote activity. Therefore, in overlap trading regions foreign exchange markets are relatively busy and it is in these regions that prices seem to fluctuate more. For example, Ito and Hashimoto (2006) examine bid-ask quotes of US dollar-Yen and Euro-US dollar and reveal that price changes seem to be large in overlapping hours. They highlight that activity for US dollar-Yen relative to Euro-US dollar is high in the Tokyo market compared to the London market suggesting that trading activity of currency pairs linked to the domestic currency may be high in the domestic foreign exchange market. Ito and Hashimoto (2006) observe that during the overlapping hours of London afternoon and New York morning, the number of deals exceeds the number of price changes highlighting another aspect of high level of trading activity in overlap trading regions. Since volatility persistence and level of trading activity is generally high in the regions created with overlapping trading hours, our finding that spill over is more pronounced from overlap trading regions is not surprising.

[6] Previous studies have also found that spill over of certain information from trading regions made up with an overlap is stronger than the spill over from the other regions. For example, Cai *et al.* (2008) find that, in the case of order flow, *EA* is the most important source of spill over to the other trading regions.

The asymmetry in volatility spill due to appreciation and depreciation of currency may be due to an interaction between trader heterogeneity in information processing and asymmetry in the information itself. For instance, exchange rate appreciation and depreciation may be regarded as asymmetric information. In the traditional framework information asymmetry arise as a result of informed and uninformed traders. In this case information asymmetry may arise due to traders interpreting currency appreciation and depreciation differently. Traders may then take positions at different points in time depending on their reaction time to process information on currency fluctuation (appreciation and depreciation). Taking positions at different points in time may be viewed as heterogeneity in information processing. Moreover, heterogeneity in information processing may result in ripple effects of trades and generate volatility. We postulate that when traders process information they react to asymmetric information differently thereby causing an asymmetric effect on volatility spill over. We find this phenomenon in the currency pair US dollar-Yen and in overlap trading regions.

Section 2 develops a model to investigate whether or not volatility in a given region is affected by information from other regions and whether or not such effects are sensitive to asymmetry in information. Sections 3 and 4 describe the data and the methodology respectively. The results are discussed in section 5. The paper finishes with concluding remarks after a robustness check of the results in section 6.

2. Model development

We consider the five trading regions: Asia (*AS*), Asia-Europe overlap (*AE*), Europe (*EU*), Europe-America overlap (*EA*) and America (*AM*) and use the regional time zones identified in Melvin and Melvin (2003). Our sample period spans from 01 August 2008 to 31 July 2009. During this sample period there exists two sub-sample periods where Europe and America daylight saving time periods overlap, one sub-sample period where daylight saving time is not applicable to both America and Europe and two sub-sample periods where daylight saving time is applicable only to America. Table 1 gives the time zones by sub-sample period and by region taking into account the daylight saving time in Europe and America.

Table 1 around here

We begin our analysis with the model where foreign exchange volatility for a given region is assumed to be dependent on its past value and the past values of other regions. We refer to this model as the bench mark model. Since the foreign exchange markets (also referred to as regions) *AS*, *EU* and *AM* and the two overlaps (also referred to as regions) *AE* and *EA* may be considered as opening and closing sequentially, the volatility of the previously open markets may be considered known. Here we assume that the past information corresponds to a maximum of lag one. In other words, for a given region the past information may be the current trading day information of some regions and the previous trading day information of the others and itself. For example, we model realised volatility for region *EA* in day *t* denoted by RV_t^{EA} as

$$RV_t^{EA} = \left(\beta_{EU,EA}, \beta_{AE,EA}, \beta_{AS,EA}, \beta_{AM,EA}, \beta_{EA,EA}\right) \begin{pmatrix} RV_t^{EU} \\ RV_t^{AE} \\ RV_t^{AS} \\ RV_{t-1}^{AM} \\ RV_{t-1}^{EA} \end{pmatrix} + \alpha X_t + \varepsilon_t^{EA} \qquad (1)$$

where *X* is a vector comprising of a constant and a dummy to control for holidays and ε is a vector of innovations. In our set up of the regional time zones *AS* starts the business day (trading day) followed by *AE*, *EU*, *EA* and *AM* in that order. Therefore, when modelling RV_t^{EA}, the past volatility of *EU*, *AE* and *AS* will be the volatility observed in the same business day which is *t* and the past volatility of *AM* and *EA* will be the volatility observed in the previous business day which is *t-1*.[7] Similarly, we model four equations for realised volatility $RV_t^{AM}, RV_t^{AS}, RV_t^{AE}$ and RV_t^{EU} for the other four regions so that together with (1) they make up a system. We consider five regions and therefore our benchmark model is a five-equation system that may be given as[8]

$$RV_t^i = \sum_{j \in S1} \beta_{j,i} RV_t^j + \sum_{j \in S2} \beta_{j,i} RV_{t-1}^j + \alpha_i X_t + \varepsilon_t^i \qquad (2)$$

[7] When modelling volatility for AM in a given business day, the past volatility of all other regions will be observed in the same business day.

[8] In the empirical analysis we consider additional lags as robustness check. In a similar study, having selected the lags based on Akaike Information Criteria (AIC), Melvin and Melvin (2003) and Cai *et al*. (2008) report that their conclusions remain unchanged when the lag structure is altered to fewer or more lags than selected under AIC.

where $i, j \in \{S = AS, AE, EU, EA$ and $AM\}$, $S1$ is the set of regions that has closed its operation in day t with respect to region i and $S2$ is the set of regions in S-$S1$. In this model the null of heat wave hypothesis is equivalent to the joint restriction of $\beta_{j,i} = 0$ for $j = i$.

To model asymmetry of information on exchange rate return we define three indicator variables based on the level of return as

$$H(h_1)_t^i = \begin{cases} 1 \text{ if exchange rate return in day } t \text{ for region } i \text{ is above } h_1 \\ 0 \text{ otherwise} \end{cases} \quad (3)$$

$$L(h_2)_t^i = \begin{cases} 1 \text{ if exchange rate return in day } t \text{ for region } i \text{ is below } h_2 \\ 0 \text{ otherwise} \end{cases} \quad (4)$$

$$N(h_1, h_2)_t^i = \begin{cases} 1 \text{ if } H(h_1)_t^i = L(h_2)_t^i = 0 \\ 0 \text{ otherwise} \end{cases} \quad (5)$$

where i = *EU*, *AE*, *AS*, *AM*, *EA* and h_1 and h_2 are thresholds. $H(h_1)_t^i$ captures the days in which the exchange rate return for region i is above the threshold h_1, $L(h_2)_t^i$ captures the days in which the exchange rate return for region i falls below the threshold h_2 and $N(h_1, h_2)_t^i$ captures the days in which the exchange rate return for region i is between h_1 and h_2. We refer to the days that belong to $H(h_1)_t^i$, $N(h_1, h_2)_t^i$ and $L(h_2)_t^i$ as high return, neutral return and low return days respectively. Alternatively, $H(h_1)_t^i$ and $L(h_2)_t^i$ may be considered as reflecting high level of appreciation and depreciation in base currency, respectively.[9] We investigate the effect of exchange rate return on volatility spill over by multiplying past volatility by the corresponding indicator variables.

Studies of exchange rate volatility spill over across regions generally reveal evidence in support of both heat wave and meteor shower hypothesis. See for example, Cai *et al.* (2008) and Melvin and Melvin (2003). Further, there is evidence to suggest that generally the meteor shower effect is more pronounced between the region in which the shock originates and the next region (Cai *et al.*, 2008). We refer to this as the nearest neighbour (region) syndrome. They also report that the heat wave effect is economically much more important than the meteor shower effect. Melvin and Melvin (2003) also report similar findings. Therefore, given the strong empirical evidence that volatility spill over is relatively more pronounced from own region's past and from the region's nearest neighbour, we

[9] For US dollar-Yen, the base and term currencies are US dollar and Yen, respectively. For Euro-US dollar, the base and term currencies are Euro and US dollar, respectively.

investigate the effect of exchange rate return asymmetry with respect to these two sources of information. For example, to investigate the effect of the level of the exchange rate return in own region's past and in the nearest neighbour on realised volatility for *EA* the volatility equation given in (1) may be augmented as

$$RV_t^{EA} = \left(\beta_{AE,EA}, \beta_{AS,EA}, \beta_{AM,EA}\right)\begin{pmatrix} RV_t^{AE} \\ RV_t^{AS} \\ RV_{t-1}^{AM} \end{pmatrix} + \left(\gamma_{EU,EA}^{H}, \gamma_{EU,EA}^{N}, \gamma_{EU,EA}^{L}\right)\begin{pmatrix} H(h_1)_t^{EU} RV_t^{EU} \\ N(h_1, h_2)_t^{EU} RV_t^{EU} \\ L(h_2)_t^{EU} RV_t^{EU} \end{pmatrix}$$

$$+\left(\gamma_{EA,EA}^{H}, \gamma_{EA,EA}^{N}, \gamma_{EA,EA}^{L}\right)\begin{pmatrix} H(h_1)_{t-1}^{EA} RV_{t-1}^{EA} \\ N(h_1, h_2)_{t-1}^{EA} RV_{t-1}^{EA} \\ L(h_2)_{t-1}^{EA} RV_{t-1}^{EA} \end{pmatrix} + \alpha X_t + \varepsilon_t^{EA} \qquad (6)$$

A system of equations for the five regions considered in this study may be specified according to the model described in (6) as

$$RV_t^i = \sum_{j \in S1_i} \beta_{j,i} RV_t^j + \sum_{j \in S2_i} \beta_{j,i} RV_{t-1}^j$$

$$+ {}_{j=S3_{i;};k=0 \text{ or } 1}\left[\gamma_{j,i}^{H} H(h_1)_{t-k}^{j} RV_{t-k}^{j} + \gamma_{j,i}^{N} N(h_1, h_2)_{t-k}^{j} RV_{t-k}^{j} + \gamma_{ji}^{L} L(h_2)_{t-k}^{j} RV_{t-k}^{j}\right]$$

$$+\left[\gamma_{i,i}^{H} H(h_1)_{t-1}^{i} RV_{t-1}^{i} + \gamma_{i,i}^{N} N(h_1, h_2)_{t-1}^{i} RV_{t-1}^{i} + \gamma_{i,i}^{L} L(h_2)_{t-1}^{i} RV_{t-1}^{i}\right]$$

$$+\alpha_i X_t + \varepsilon_t^i \qquad (7)$$

where $S1_i$ is the set of regions that closed trading in day *t* relative to region *i* and not including the nearest neighbour (region) of region i, $S2_i$ is the set of regions that has not commenced trading in day *t* relative to region i, $S3_i$ is the nearest neighbour (region) of region i, *k=0* if $S3_i$ has already closed its operation in day *t* and *k=1* otherwise.

In the five-equation system specified in (7) the null hypothesis to test the heat wave hypothesis in the own region is $\gamma_{i,i}^{H} = \gamma_{i,i}^{N} = \gamma_{i,i}^{L} = 0$ against the alternative of at least one of γ_{ii}^{H}, $\gamma_{i,i}^{N}$ and $\gamma_{i,i}^{L}$ is not zero. To investigate the asymmetric effect of exchange rate return on volatility spill over in the own region, we test the hypothesis $\gamma_{i,i}^{H} = \gamma_{i,i}^{L}$ against $\gamma_{i,i}^{H} \neq \gamma_{i,i}^{L}$. To investigate the meteor shower hypothesis in the nearest neighbour region, we test $\gamma_{j,i}^{H} = \gamma_{j,i}^{N} = \gamma_{j,i}^{L} = 0$ against the alternative of at least one of $\gamma_{j,i}^{H}$, $\gamma_{j,i}^{N}$ and $\gamma_{j,i}^{L}$ is not zero where $j = S3_i$. We test the asymmetric effect of exchange rate return on volatility spill over from the nearest neighbour region in the null hypothesis of $\gamma_{j,i}^{H} = \gamma_{j,i}^{L}$ against $\gamma_{j,i}^{H} \neq \gamma_{j,i}^{L}$ where $j = S3_i$.

3. Data

The data used here is intra-daily US dollar-Japanese Yen and Euro-US dollar exchange rate from Electronic Broking Systems of ICAP and spans 1 August 2008 to 31 July 2009. This covers the latest one year at the time when we launched this research. Data in weekends are excluded. Following Berger *et al*. (2009), we drop several holidays and days of unusually light volume near these holidays: December 24–26, December 31–January 2, Good Friday, Easter Monday, Memorial Day, Labour Day, Thanks giving day and the day following, and July 4.

The data set is created from periods of one-second time slices comprised of a Price Record and a Deal Record. The Price Record lists the EBS best bid/ask prices at the end of a time slice. We convert the original dataset into 5-minute intervals.[10] The return, R_{t} of a currency pair is computed as $R_{\mathrm{t}} = 100 \times [\ln(S_t) - \ln(S_{t-1})]$ where S_t. is price in period *t*. Price is computed as the mid-point quote of the best bid and ask rates observed in the interval concerned. We use sum of squared returns as realized volatility.

4. Methodology

The regression equations given in (2) and (7) model realised volatility in the exchange rate return in a given region as a function of past volatility in the given region and past volatility of the other regions.[11] The structure (number of lags) of each of the five equations (one equation per region) in the system is the same and therefore we estimate the five-equation system as a VAR model. These VAR systems are estimated with the seemingly unrelated regression (SUR) method. To determine the thresholds h_1 and h_2 we consider the 5-minute normalized exchange rate returns of all five regions

[10] Andersen and Bollerslev (1998) recommend this frequency for calculation of realized volatility.

[11] The timing of the past volatility in other regions will differ according to the sequential position of the region relative to the region for which realised volatility is modelled.

over the full sample period.[12] Then we set h_1 and h_2 as percentiles of the normalised returns. The percentiles considered for (h_1, h_2) are (60^{th}, 40^{th}), (70^{th}, 30^{th}) and (90^{th}, 10^{th}).

The realised volatility in the day is measured as the sum of squared intraday returns. As shown in Table 1, the regions do not have the same time span. Therefore, to account for the disparity in the time span we standardise the measure of realised volatility by the number of 5-minute intervals in the time span corresponding to the region.

Exchange rates are susceptible to news and therefore exchange rate volatility could have outliers. Some studies control for such news events by identifying major exchange rate events such as trade wars and interest rate cuts and introducing dummies in the volatility equation. We address this problem by taking the logarithm of realised volatility.[13] To investigate how a shock to one region may impact the volatility in another region we examine the cumulative impulse response.

5. Results and discussion

5.1 Heat wave hypothesis, nearest neighbour syndrome and meteor shower hypothesis

We discuss the results obtained in the estimation of the benchmark model given in (2) first. Table 2 and Table 3 report the Wald test statistic and the associated *p*-value for US dollar-Yen and Euro-US dollar volatility respectively. The shaded cell in a given column in Tables 2 and 3 corresponds to the nearest neighbour (region) of the dependent region. The diagonal cells in Tables 2 and 3 correspond to the dependent region and its immediate past. The bottom rows in Tables 2 and 3 report the adjusted-R square and *p*-values of *Q*-statistics on residual correlation for lag 5 and lag 35 for each equation in the five-equation system specified in (2).

Table 2 around here

The diagonal entries in Table 2 reveal statistical evidence (at the 5% level) in favour of the heat wave hypotheses for US dollar-Yen volatility in two (Asia and Asia-Europe overlap) of the five regions. Off-diagonal elements provide strong support for the meteor shower hypothesis with 15 of

[12] The exchange rate return is normalized to adjust for the difference in trading hours of the trading regions.

[13] Melvin and Melvin (2003) highlight that taking the logarithm in the realized volatility not only address the problem of outliers but, to a certain extent, the non-normality in realized volatility as well.

the 20 off-diagonal cells revealing statistical evidence at the 5% level. Further, in each equation we observe that the test statistic is the largest in the cell corresponding to the region that we refer to as the nearest neighbour. In other words, our data reveal very strong evidence in support of the nearest neighbour syndrome.

Table 3 around here

For Euro-US dollar volatility, we find that the evidence in favour of the heat wave hypothesis is stronger. Here, three (Asia, Europe and Europe-America) out of the five regions provide statistical evidence at the 5% level. The evidence in support of the meteor shower hypothesis for Euro-US dollar volatility is also available in Table 3. Fourteen of the 20 off-diagonal elements in Table 3 are statistically significant at the 10% level. In this case very strong evidence in support of the nearest neighbour syndrome is observed in three of the five regions. For Asia and Europe-America overlap the Wald test statistic is significant at the 1% level however, they are not the largest in the relevant column.[14]

Tables 4 and 5 report cumulative impulse response of US dollar-Yen and Euro-US dollar realised volatility to a shock in a given region. The aim here is to get further insights into volatility linkages across trading regions. The reported cumulative impulse response is the sum of responses over 200 consecutive periods. The impulse response is computed with one unit shock in the innovation in model (2). Here, the largest response due to the impulse is observed in the diagonal elements. This indicates that the response to the own period's immediate past is greater than the response to that of the other regions. Further, there is evidence that the second largest cumulative response is associated with the nearest neighbour. With US dollar-Yen volatility, the second largest cumulative response is observed in the nearest neighbours of *AE*, *EU* and *AM* and with Euro-US dollar volatility the second largest cumulative response is observed in the nearest neighbours of *AE* and *EU*. In terms of cumulative impulse response, both currency pairs reveal that the evidence of the nearest neighbour syndrome is strong in the *AE* and *EU* regions.

Table 4 around here

[14] To conclude that nearest neighbour syndrome is strongly supported in a given region, we require the relevant Wald test statistic to be the largest in the column associated with that region.

Overall, we find strong evidence in favour of the heat wave hypothesis and of the nearest neighbour syndrome especially in the *AE* and *EU* regions. These findings pave the way for our main investigation of the effect of exchange rate change asymmetry on volatility linkages across trading regions.

Table 5 around here

5.2 Effect of exchange rate return on volatility spill over

As outlined in section 4, to investigate whether or not asymmetry of exchange rate return has an impact on volatility spill over, we classify each day as high, neutral or low based on a pair of pre-specified percentiles on normalised returns of the exchange rate. The investigation is carried out with three pairs of percentiles: (60^{th}, 40^{th}), (70^{th}, 30^{th}) and (90^{th}, 10^{th}). In this section we discuss the results obtained with the pair of percentiles (70^{th}, 30^{th}). The results obtained with the other two pairs of percentiles are discussed in section 6.1 as robustness check.

US dollar-Yen volatility

Table 6 reports the parameters estimated in model (7) for US dollar-Yen volatility. Panel A of Table 6 reports the parameters estimated for the regions for which the effect of exchange rate return is not modelled. Panels B and C of Table 6 report the parameters associated with the nearest neighbour region's past volatility and the parameters associated with the own region's past volatility respectively.

In Table 2 we observe that in the case of US dollar-Yen volatility, the nearest neighbour syndrome is supported in all five regions. When we partition the information (realised volatility) of the nearest neighbour region into three components according to the level of the return in the exchange rate, we observe in Panel B of Table 6 that the parameters associated with each of the three components of all five regions are also highly statistically significant. Moreover, the coefficient associated with NN-Low (exchange rate return of the nearest neighbour region is below the 30^{th} percentile) is larger than the coefficient associated with NN-High (exchange rate return of the nearest neighbour region is above the 70th percentile) in all five regions suggesting a possible asymmetric effect of exchange rate return on volatility spill over from the nearest neighbour region. However, this asymmetric effect is statistically significant (at the 5% level) only in the two regions *AE* and *EA*.[15]

Panel C of Table 6 reports the parameters associated with the own period's past information suitably modified to reflect three levels of exchange rate return (high, neutral and low). In Table 2 we observe that own past information of the two regions *AS* and *AE* does have an effect on current period volatility. Here also we see that when the effect of the own region's past information is statistically significant the effect of the three components: OWN-previous-High, OWN-previous-Neutral and OWN-previous-Low are also statistically significant. Entries in Table 2 reveal that previous period volatility of the three regions *EU*, *EA* and *AM* does not affect the volatility in the current period. However, once the exchange rate return level is incorporated with past volatility to form a three component-information set for *EU*, the three components become statistically significant. Panel C of Table 6 reveals further that even though the coefficients of OWN-previous-High and the coefficients of OWN-previous-Low are statistically significant for some regions (*AS*, *AE* and *AU*), they do not reveal a consistent pattern of an asymmetric effect. The difference in the coefficients associated with OWN-previous-High and OWN-previous-Low in these regions is also not statistically significant. These observations suggest that the effect of the level of exchange rate return in the heat wave of *EU*, *AS* and *AE* may be symmetric. Decomposition of past volatility for *EA* and *AM* does not have a statistically significant effect on current period volatility. The diagonal elements of Table 2 reveal that both these regions do not support the heat wave hypothesis.

Table 6 around here

To give an economic interpretation of these results we report in Table 7 the cumulative impulse response (first 200 responses) calculated with one unit shock in innovation in the asymmetric model given in (7). Panel A (B) of Table 7 corresponds to the left (right) -hand side cases in Figure 1. The results reveal that the effect of volatility spill over is generally greater when the exchange rate return is low in the nearest neighbour region than when the exchange rate return is high in the nearest

[15] The test results for asymmetry discussed in this sub-section are available upon request.

neighbour region. Again, the evidence of asymmetry in response to a given shock in the nearest neighbour region is most pronounced in the two regions *AE* (0.1=0.87-0.77) and *EA* (0.14=1.14-1.00).

Table 7 around here

Figure 1 shows the cumulative impulse response function for US dollar-Yen volatility for 10 days. The panels on the left-hand side in Figure 1 give the response of a given region to its nearest neighbour while the panels on the right-hand side of Figure 1 show the impulse response function of a given region to its own past. In the panels on the left-hand side, NN-High and NN-Low, occurs once only at nearest neighbour and the other segments are fixed at NN-Neutral. In the panels on the right-hand side, we assume that each of the two cases, OWN-previous-High and OWN-previous-Low occurs once only in the own region in the previous day and the other regions are fixed at OWN-previous-Neutral. Consistent with the cumulative impulse response over 200 days reported in Table 7, the panels on the left-hand side show that the nearest neighbour syndrome is more pronounced when the exchange rate return is low (NN-Low) than when it is high (NN-High). The asymmetric effect appears to be more pronounced in the regions corresponding to an overlap. That is, the regions that reveal strong asymmetric effect of exchange rate return on volatility spill over are *AE* and *EA*. Trading activity of foreign exchange markets is generally high in overlap regions.[16] The panels on the right-hand side of Figure 1 confirm the observation in Panel C of Table 6 that the effect of exchange rate return on volatility spill over from the own region may not be asymmetric.

Figure 1 around here

Euro-US dollar volatility

The effect of exchange rate return on realised volatility spill over for the currency pair Euro-US dollar is reported in Table 8. Panel A of Table 8 report for each dependent region the parameters associated with past period information from all regions other than from the own and from the nearest neighbour regions. We consider the own region's and the nearest neighbour region's exchange rate return to

[16] Iwatsubo and Kitamura (2009) investigate intraday Yen/US dollar exchange rate over the period 1987 to 2007, and report that cumulative price change in over lapping business hours of the London and New York markets is the most persistent and is the highest contributor to daily exchange rate fluctuation among the market segments London, London-New York overlap, New York and Pacific.

investigate whether there is an asymmetric effect of exchange rate return on volatility spill over. Panel B of Table 8 present the parameters associated with the three components of past information of the nearest neighbour and Panel C of Table 8 gives the parameters corresponding to the three components associated with the past period information of the own region. Here, as in the case with US dollar-Yen, we find that all three components of the nearest neighbour region (NN-High, NN-Neutral and NN-Low) are highly statistically significant. However, the evidence of an asymmetric effect of exchange rate return on volatility spill over from the nearest neighbour region is not consistent. Only in regions *EU*, *EA* and *AM* we observe that the coefficient of NN-Low is larger than that of NN-High. Statistically significant difference between NN-Low and NN-High is observed in the *AM* region.

In Table 3 we observe that heat wave hypothesis is not supported in *AE* and *AM* for Euro-US dollar volatility. Not surprisingly, when we partition the past information of these two regions based on the level of exchange rate return, Panel C of Table 8 reveal that the components themselves are not statistically significant.[17]

Table 8 around here

Cumulative impulse response functions for Euro-US dollar for ten days are presented in Figure 2. The left-hand side panels in Figure 2 show the cumulative impulse response of a given region to a shock in its nearest neighbour region. The right-hand side panels in Figure 2 give the cumulative impulse response of a given region to a shock from itself in the past period. Unlike in the case with US dollar-Yen, Figure 2 does not reveal any consistent pattern to suggest an asymmetric effect of exchange rate return on volatility spill over either from the nearest neighbour region or from the own region.

Figure 2 around here

Table 9 reports the cumulative impact of a unit shock in the nearest neighbour region and in own region's past at three levels of exchange rate return: high, neutral and low. Panel A of Table 9 present

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[17] Panel D in Tables 6 and 8 report the adjusted R-square and the *p*-values of Q-statistics for residual autocorrelation for lags 5 and 35. Except for region *AM* in the case of Euro-US dollar, the adjusted R-square is at least 39% suggesting that the model that we have formulated in (7) has moderate explanatory power. These R-square values are comparable to those reported in similar studies such as Cai *et al.* (2008).

the results associated with a shock in the nearest neighbour region and Panel B of Table 9 present the results associated with a shock in the own region. Here, the cumulative impulse response (first 200 responses) is calculated with one unit shock in innovation in the asymmetric model given in (7). The findings here are consistent with the cumulative impulse response functions reported in Figure 2 that in the currency pair Euro-US dollar, there is no evidence of a consistent pattern of asymmetric effect of exchange rate return on volatility spill over from the nearest neighbour region or from the own region.

Overall, the evidence in the period that we sampled suggest that (i) depreciation in the exchange rate tends to affect volatility spill over more than appreciation and (ii) the asymmetric effect of exchange rate return on volatility spill over is more likely to be found from the nearest neighbour region created with an overlap in business hours. We uncover this in the currency pair US dollar-Yen and not in Euro-US dollar. Our sample period overlaps with the subprime crisis period. Therefore, our finding of asymmetric effect of exchange rate return on volatility spill over in one currency pair and not in the other may be attributed to foreign exchange trader sentiment during the subprime crisis period. During the subprime crisis Japanese Yen deemed relatively safe compared to the Euro and the US dollar. Therefore, depreciation in the US dollar during the subprime crisis induced pressure on the traders to sell the currency and seek alternative currencies (in our case the Yen) that were relatively safe. The market then experienced large negative returns resulting in high volatility that would eventually spill over to the other regions- especially to the next region. This postulation is consistent with the results of Panel A in Table 7.

Table 9 around here

6. Robustness check

The results discussed in this section are not reported for brevity and are available upon request from the corresponding author.

6.1 Sensitivity to different thresholds

Here we discuss the results with two alternative specifications of thresholds (60^{th}, 40^{th}) and (90^{th}, 10^{th}) percentiles. In the case of US dollar-Yen, when we use (60^{th}, 40^{th}) percentiles as the thresholds that classify exchange rate return as high, neutral and low, our conclusions remain largely unchanged.[18] The only exception is that no statistical significance of OWN-previous-High, OWN-previous-Neutral and OWN-previous-Low is observed for the *EU* region. The same observation is made when the thresholds are assumed as (90th, 10th) percentiles. The parameters estimated with (90th, 10th) percentiles as the thresholds reveal further that statistical evidence of spill over of return induced volatility for the nearest neighbour and own past for region *AE* is found only when the level of exchange rate return is classified as low. The observations here suggests that asymmetry in volatility spill over due to the effects of exchange rate return may be sensitive to the level of the exchange rate return. Consistent evidence of asymmetry in volatility spill over for US dollar-Yen is observed only from the nearest neighbour of region *EA*.

When we repeat the analysis with the two new sets of thresholds for the Euro-US dollar data, the results concur with the findings when (70th, 30th) percentiles are used as the thresholds. That is, in the case of Euro-US dollar evidence of an asymmetric effect of exchange rate return on volatility spill over from the nearest neighbour region or from the own region is not found.

6.2 Two exchange rate return regimes

We check robustness of the results by having asymmetry in the return classified as: positive (exchange rate return is positive) and negative (exchange rate return is negative) as well. The model used here is

$$RV_t^i = \sum_{j \in S1_i} \beta_{j,i} RV_t^j + \sum_{j \in S2_i} \beta_{j,i} RV_{t-1}^j + {}_{j=S3_{i;};k=0 \text{ or } 1} \left[\gamma_{j,i}^P P_{t-k}^j RV_{t-k}^j + \gamma_{ji}^N N_{t-k}^j RV_{t-k}^j\right]$$

$$+\left[\gamma_{i,i}^P P_{t-1}^i RV_{t-1}^i + \gamma_{i,i}^N N_{t-1}^i RV_{t-1}^i\right] + \alpha_i X_t + \varepsilon_t^i \qquad (8)$$

where

$$P_t^i = \begin{cases} 1 \text{ if exchange rate return in day } t \text{ for region } i \text{ is positive} \\ 0 \text{ otherwise} \end{cases} \qquad (9)$$

$$N_t^i = 1 - P_t^i \qquad (10)$$

[18] The model estimated here is given in (7). In section 5.2, we use (70th, 30th) percentiles as the thresholds.

$S1_i$ is the set of regions that closed trading in day *t* relative to region *i* and not including the nearest neighbour (region) of region i, $S2_i$ is the set of regions that has not commenced trading in day *t* relative to region *i*, $S3_i$ is the nearest neighbour (region) of region *i*, *k=0* if $S3_i$ has already closed its operation in day *t* and *k=1* otherwise. The results under this classification are the same for US dollar-Yen and Euro-US dollar. In both currency pairs we observe no evidence of any asymmetry in volatility spill over from the nearest neighbour or from the own region due to appreciation or depreciation in the exchange rate. Here we find that volatility spill over may not be sensitive to information such as depreciation or appreciation of the exchange rate. Evidence elsewhere suggests that the level of appreciation or depreciation in the exchange rate affect volatility spill over from the nearest neighbour of trading regions made up of an overlap.

6.3 An alternative model specification

Previously we modelled asymmetry in volatility spill over from the nearest neighbour region and from the own region only. Here we discuss the results when asymmetric effect of exchange rate return on volatility spill over is modelled for all regions. In this case a system of equations for the five regions may be specified as

$$RV_t^i = \sum_{j \in S4_i} \left[\gamma_{j,i}^H H(h_1)_t^j RV_t^j + \gamma_{j,i}^N N(h_1, h_2)_t^j RV_t^j + \gamma_{ji}^L L(h_2)_t^j RV_t^j\right]$$

$$+ \sum_{j \in S2_i} \left[\gamma_{j,i}^H H(h_1)_{t-1}^j RV_{t-1}^j + \gamma_{j,i}^N N(h_1, h_2)_{t-1}^j RV_{t-1}^j + \gamma_{ji}^L L(h_2)_{t-1}^j RV_{t-1}^j\right]$$

$$+ \left[\gamma_{i,i}^H H(h_1)_{t-1}^i RV_{t-1}^i + \gamma_{i,i}^N N(h_1, h_2)_{t-1}^i RV_{t-1}^i + \gamma_{i,i}^L L(h_2)_{t-1}^i RV_{t-1}^i\right] + \alpha_i X_t + \varepsilon_t^i \quad (11)$$

where $S4_i$ is the set of regions that closed trading in day *t* relative to region i, $S2_i$ is the set of regions that has not commenced trading in day *t* relative to region i and $H(h_1)_t^i$, $N(h_1, h_2)_t^i$ and $L(h_2)_t^i$ are defined in (3)-(5).

When the (70th, 30th) percentiles are used as the thresholds, the results reveal no evidence of an asymmetric effect of exchange rate return on volatility spill over for Euro-US dollar. For the currency pair US dollar-Yen, evidence of asymmetry in volatility spill over is observed in regions *AE* and *EA*. For *EA*, the asymmetry is observed in the spill over from the nearest neighbour region (*EU*) and from

AM. *EA* is the overlap of these two regions. Asymmetry in spill over to region *AE* is observed from *EU* and *EA*. *AE* is made up of the overlap between *AS* and *EU*. In this specification, we find no evidence of an asymmetry in spill over from *AS* (the nearest neighbour of *AE*) to *AE*. The results here concur with the pervious finding that asymmetry in volatility spill over is more likely to be observed in the regions corresponding to an overlap than otherwise.

7. Conclusion

This study investigates whether the level of foreign exchange return has an effect on spill over of foreign exchange return volatility across five trading regions: Asia, Asia-Europe overlap, Europe, Europe-America overlap and America identified in Melvin and Melvin (2003) and using intra-day returns of the currency pairs: US dollar-Yen and Euro-US dollar. We treat level of exchange rate return as asymmetric information and the response to such information by the traders as heterogeneous and hypothesise that the interaction of information asymmetry and trader heterogeneity may have an asymmetric effect on volatility spill over. To test this hypothesis we model information asymmetry and volatility together by integrating the level of exchange rate return on exchange rate return volatility through indicator variables.

In the currency pair US dollar-Yen, we find that volatility spill over from the nearest region is sensitive to the level of exchange rate return such that depreciation in the US dollar against the Yen induce a greater effect on the volatility spill over than appreciation in the US dollar against the Yen. This asymmetric spill over effect is stronger from the regions created with overlapping operational time.

We do not find an asymmetric volatility spill over effect for the currency pair Euro-US dollar. Different currency pairs may have unique relationships across trading regions. Therefore, the finding with the US dollar-Yen currency pair may not be generalised to all currency pairs. However, our sample period has a considerable overlap with the subprime crisis period and therefore the results have to be interpreted with caution. We propose investigation of the effect of exchange rate return on volatility spill over across trading regions with a different data set as a future study.

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Table 1. Regional time zones

Region	*EU* and *AM* daylight saving time	No daylight saving time	AM daylight saving time
	Sub-sample period		
	01/8/08-26/10/08 29/3/09-31/07/09	03/11/08-07/03/09	27/10/08-02/11/08 08/03/09-28/03/09
AS	23:30-05:30	23:30-06:30	23:30-06:30
AE	05:30-08:00	06:30-08:00	06:30-08:00
EU	08:00-11:30	8:00-12:30	08:00-11:30
EA	11:30-15:30	12:30-16:30	11:30-16:30
AM	15:30-20:00	16:30-21:00	16:30-20:00

Notes: Time line is GMT. *AS* = Asia, *AE* = Asia and Europe overlap, *EU* = Europe, *EA* = Europe and America overlap and *AM* = America.

Table 2. Heat wave and meteor shower effects for US dollar-Yen volatility

Independent region	Dependent region				
	AS	*AE*	*EU*	*EA*	*AM*
AS	3.86**	29.48***	4.85**	2.62	4.16**
	(0.049)	(0.000)	(0.028)	(0.106)	(0.041)
AE	4.85**	6.73***	29.57***	6.06**	2.09
	(0.028)	(0.009)	(0.000)	(0.014)	(0.148)
EU	1.46	6.04**	2.51	22.16***	3.97**
	(0.227)	(0.014)	(0.113)	(0.000)	(0.046)
EA	6.05**	0.76	6.09**	0.19	39.50***
	(0.014)	(0.383)	(0.014)	(0.665)	(0.000)
AM	13.61***	1.85	10.69***	9.82***	0.90
	(0.000)	(0.174)	(0.001)	(0.002)	(0.342)
Adj. R-square	0.45	0.38	0.47	0.41	0.40
p-Value, *Q*(5)	0.33	0.13	0.76	0.20	0.32
p-Value, *Q*(35)	0.82	0.40	0.11	0.57	0.34

Notes: *AS* = Asia, *AE* = Asia and Europe overlap, *EU* = Europe, *EA* = Europe and America overlap and *AM* = America. The system of volatility equations considered here is: $RV_t^i = \sum_{j\in S1} \beta_{j,i} RV_t^j + \sum_{j\in S2} \beta_{j,i} RV_{t-1}^j + \alpha_i X_t + \varepsilon_t^i$ where *i*∈*{S=AS, AE, EU, EA* and *AM}*, *S*1 is the set of regions that has closed its operation in day *t* and *S2* is the set of regions in *S-S1*. The shaded cell in a given column corresponds to the nearest neighbour (region) of the dependent region. The figures are the Wald statistics and the numbers in parenthesis are p-values. *** refers to significance at the 1 per cent level and ** refers to significance at the 5 per cent level.

Table 3. Heat wave and meteor shower effects for Euro-US dollar volatility

Independent region	Dependent region				
	AS	*AE*	*EU*	*EA*	*AM*
AS	27.06***	42.08***	11.90***	1.72	2.90*
	(0.000)	(0.000)	(0.001)	(0.189)	(0.088)
AE	10.81***	1.53	18.63***	27.29***	3.11*
	(0.001)	(0.216)	(0.000)	(0.000)	(0.078)
EU	0.13	8.75***	3.99**	13.20***	5.27**
	(0.723)	(0.003)	(0.046)	(0.000)	(0.022)
EA	2.46	4.98**	6.13**	16.38***	9.22***
	(0.117)	(0.026)	(0.013)	(0.000)	(0.002)
AM	22.85***	2.24	0.82	1.00	1.63
	(0.000)	(0.135)	(0.365)	(0.316)	(0.202)
Adj. R-square	0.57	0.45	0.40	0.48	0.27
p-Value, *Q*(5)	0.08	0.25	0.48	0.65	0.45
p-Value, *Q*(35)	0.02	0.71	0.33	0.04	0.58

Notes: *AS* = Asia, *AE* = Asia and Europe overlap, *EU* = Europe, *EA* = Europe and America overlap and *AM* = America. The system of volatility equations considered here is: $RV_t^i = \sum_{j\in S1} \beta_{j,i} RV_t^j + \sum_{j\in S2} \beta_{j,i} RV_{t-1}^j + \alpha_i X_t + \varepsilon_t^i$ where *i*∈{*S*=*AS*, *AE*, *EU*, *EA* and *AM*}, *S*1 is the set of regions that has closed its operation in day *t* and *S2* is the set of regions in *S-S1*. The shaded cell in a given column corresponds to the nearest neighbour (region) of the dependent region. The figures are the Wald statistics and the numbers in parenthesis are p-values. *** refers to significance at the 1 per cent level, ** refers to significance at the 5 per cent level and * refers to significance at the 10 per cent level.

Table 4. Cumulative impulse response of US dollar-Yen volatility

Independent region	Dependent region				
	AS	*AE*	*EU*	*EA*	*AM*
AS	1.75 (0.197)	0.81 (0.174)	0.80 (0.196)	0.73 (0.189)	0.84 (0.216)
AE	1.09 (0.299)	1.95 (0.252)	1.27 (0.288)	1.09 (0.280)	1.13 (0.308)
EU	0.87 (0.275)	0.78 (0.234)	1.88 (0.265)	1.05 (0.254)	1.05 (0.288)
EA	0.95 (0.237)	0.68 (0.203)	0.90 (0.226)	1.77 (0.220)	1.22 (0.255)
AM	0.87 (0.219)	0.62 (0.180)	0.81 (0.202)	0.79 (0.200)	1.78 (0.227)

Notes: *AS* = Asia, *AE* = Asia and Europe overlap, *EU* = Europe, *EA* = Europe and America overlap and *AM* = America. The system of volatility equations considered here is: $RV_t^i = \sum_{j \in S1} \beta_{j,i} RV_t^j + \sum_{j \in S2} \beta_{j,i} RV_{t-1}^j + \alpha_i X_t + \varepsilon_t^i$ where *i*∈{*S*=*AS*, *AE*, *EU*, *EA* and *AM*}, $S1$ is the set of regions that has closed its operation in day *t* and *S2* is the set of regions in *S*-*S1*. Cumulative response is the sum of first 200 period impulse responses. Impulse response is calculated with one unit shock in innovation ε_t^i. Numbers in parenthesis are standard errors obtained with 1,000 residual bootstrap replications. The shaded cell in a given column corresponds to the nearest neighbour (region) of the dependent region.

Table 5. Cumulative impulse response of Euro-US dollar volatility

Independent region	Dependent region				
	AS	*AE*	*EU*	*EA*	*AM*
AS	2.45	1.08	1.07	1.08	1.04
	(0.317)	(0.220)	(0.235)	(0.255)	(0.254)
AE	1.90	2.21	1.50	1.72	1.47
	(0.471)	(0.311)	(0.332)	(0.369)	(0.365)
EU	0.95	0.78	1.82	1.02	0.94
	(0.333)	(0.225)	(0.235)	(0.264)	(0.266)
EA	1.22	0.86	0.94	2.14	1.12
	(0.382)	(0.257)	(0.271)	(0.304)	(0.308)
AM	1.01	0.57	0.57	0.61	1.62
	(0.251)	(0.166)	(0.171)	(0.197)	(0.189)

Notes: *AS* = Asia, *AE* = Asia and Europe overlap, *EU* = Europe, *EA* = Europe and America overlap and *AM* = America. The system of volatility equations considered here is: $RV_t^i = \sum_{j \in S1} \beta_{j,i} RV_t^j + \sum_{j \in S2} \beta_{j,i} RV_{t-1}^j + \alpha_i X_t + \varepsilon_t^i$ where *i*∈*{S=AS, AE, EU, EA* and *AM}*, *S*1 is the set of regions that has closed its operation in day *t* and *S2* is the set of regions in *S-S1*. Cumulative response is the sum of first 200 period impulse responses. Impulse response is calculated with one unit shock in innovation ε_t^i. Numbers in parenthesis are standard errors obtained with 1,000 residual bootstrap replications. The shaded cell in a given column corresponds to the nearest neighbour (region) of the dependent region.

Table 6. Effect of previous period exchange rate return on volatility spill over when exchange rate return is modelled with own region's and nearest neighbour region's past volatility: US dollar-Yen

Thresholds used for h_1 and h_2 are 70th and 30th percentiles										
Independent region	**Dependent region**									
	AS		*AE*		*EU*		*EA*		*AM*	
Panel A										
AS	OWN		NN		0.11 (0.03)		0.09 (0.11)		0.14 (0.03)	*
AE	0.18 (0.03)	*	OWN		NN		0.20 (0.00)	*	0.12 (0.13)	
EU	0.10 (0.22)		0.15 (0.01)	*	OWN		NN		0.16 (0.04)	*
EA	0.21 (0.01)	*	0.06 (0.35)		0.15 (0.02)	*	OWN		NN	
AM	NN		0.07 (0.16)		0.16 (0.00)	*	0.18 (0.00)		OWN	
Panel B										
NN-High	0.21 (0.01)	*	0.22 (0.00)	*	0.35 (0.00)	*	0.28 (0.00)	*	0.41 (0.00)	*
NN-Neutral	0.23 (0.00)	*	0.25 (0.00)	*	0.36 (0.00)	*	0.31 (0.00)	*	0.44 (0.00)	*
NN-Low	0.24 (0.00)	*	0.26 (0.00)	*	0.37 (0.00)	*	0.34 (0.00)	*	0.45 (0.00)	*
Panel C										
OWN-previous-High	0.13 (0.02)	*	0.15 (0.02)	*	0.12 (0.06)	*	0.04 (0.55)		0.04 (0.60)	
OWN-previous-Neutral	0.10 (0.04)	*	0.18 (0.00)	*	0.10 (0.10)	*	0.03 (0.68)		0.06 (0.36)	
OWN-previous-Low	0.12 (0.04)	*	0.15 (0.02)	*	0.12 (0.06)	*	0.02 (0.74)		0.06 (0.35)	
Panel D										
Adj. R-square	0.45		0.39		0.47		0.42		0.40	
p-Value, *Q*(5)	0.34		0.08		0.73		0.17		0.34	
p-Value, *Q*(35)	0.82		0.28		0.11		0.44		0.52	

Notes: *AS* = Asia, *AE* = Asia and Europe overlap, *EU* = Europe, *EA* = Europe and America overlap and *AM* = America. The system of volatility equations estimated here is given in (7). To determine the thresholds h_1 and h_2 we consider the normalised daily exchange rate returns of all five regions over the full sample period. Then we set h_1 and h_2 as a percentile of the normalised returns. NN= nearest neighbour (region) and OWN= own region. The figures in Panel A-C are estimated parameters. The numbers in the parentheses are *p*-values. * refers to significance at the 10 percent level.

Table 7. Cumulative impulse response with the asymmetric effect model for US dollar-Yen volatility

Thresholds used for h_1 and h_2 are 70th and 30th percentiles

	Dependent region				
	AS	*AE*	*EU*	*EA*	*AM*
Panel A					
NN-High	0.85 (0.212)	0.77 (0.182)	1.37 (0.322)	1.00 (0.248)	1.16 (0.268)
NN-Neutral	0.88 (0.203)	0.84 (0.182)	1.40 (0.319)	1.07 (0.247)	1.23 (0.265)
NN-Low	0.90 (0.210)	0.87 (0.195)	1.43 (0.323)	1.14 (0.260)	1.25 (0.275)
Panel B					
OWN-previous-High	1.85 (0.213)	1.99 (0.278)	1.97 (0.266)	1.82 (0.247)	1.76 (0.225)
OWN-previous-Neutral	1.80 (0.202)	2.05 (0.282)	1.93 (0.252)	1.80 (0.238)	1.80 (0.218)
OWN-previous-Low	1.84 (0.217)	1.99 (0.275)	1.97 (0.264)	1.79 (0.241)	1.81 (0.227)

Notes: *AS* = Asia, *AE* = Asia and Europe overlap, *EU* = Europe, *EA* = Europe and America overlap and *AM* = America. The system of volatility equations estimated here is given in (7). To determine the thresholds h_1 and h_2 we consider the normalised daily exchange rate returns of all five regions over the full sample period. Then we set h_1 and h_2 as a percentile of the normalised returns. Cumulative response is the sum of first 200 period impulse responses. Impulse response is calculated with one unit shock in innovation in equation (7). Numbers in parenthesis are standard errors obtained with 1,000 residual bootstrap replications. In Panel A, we assume that each of the two cases, “High” and “Low”, occurs once only at nearest neighbour and the other segments are fixed at “Neutral”. In Panel B, we assume that each of the two cases, “High” and “Low”, occurs once only in the own region in the previous day and the other regions are fixed at “Neutral”.

Table 8. Effect of previous period exchange rate return on volatility spill over when exchange rate return is modelled with own region's and nearest neighbour region's past volatility: Euro-US dollar

Thresholds used for h_1 and h_2 are 70th and 30th percentiles										
Independent region	**Dependent region**									
	AS		*AE*		*EU*		*EA*		*AM*	
Panel A										
AS	OWN		NN		0.16	*	0.05 (0.32)		0.12 (0.06)	*
AE	0.34 (0.00)	*	OWN		NN		0.38 (0.00)	*	0.16 (0.12)	
EU	0.02 (0.76)		0.16 (0.00)	*	OWN		NN		0.21 (0.01)	*
EA	0.14 (0.09)	*	0.11 (0.03)	*	0.15 (0.01)	*	OWN		NN	
AM	NN		0.06 (0.15)		0.03 (0.49)		0.04 (0.35)		OWN	
Panel B										
NN-High	0.28 (0.00)	*	0.28 (0.00)	*	0.33 (0.00)	*	0.20 (0.00)	*	0.25 (0.01)	*
NN-Neutral	0.29 (0.00)	*	0.25 (0.00)	*	0.32 (0.00)	*	0.22 (0.00)	*	0.27 (0.00)	*
NN-Low	0.26 (0.00)	*	0.25 (0.00)	*	0.34 (0.00)	*	0.21 (0.00)	*	0.30 (0.00)	*
Panel C										
OWN-previous-High	0.18 (0.00)	*	0.09 (0.18)		0.14 (0.03)	*	0.22 (0.00)	*	0.06 (0.35)	
OWN-previous-Neutral	0.23 (0.00)	*	0.09 (0.16)		0.13 (0.04)	*	0.23 (0.00)	*	0.08 (0.20)	
OWN-previous-Low	0.19 (0.00)	*	0.10 (0.15)		0.16 (0.01)	*	0.24 (0.00)	*	0.08 (0.23)	
Panel D										
Adj. R-square	0.57		0.45		0.40		0.48		0.27	
p-Value, *Q*(5)	0.17		0.23		0.47		0.69		0.38	
p-Value, *Q*(35)	0.01		0.58		0.29		0.03		0.33	

Notes: *AS* = Asia, *AE* = Asia and Europe overlap, *EU* = Europe, *EA* = Europe and America overlap and *AM* = America. The system of volatility equations estimated here is given in (7). To determine the thresholds h_1 and h_2 we consider the normalised daily exchange rate returns of all five regions over the full sample period. Then we set h_1 and $h_2$as a percentile of the normalised returns. NN= nearest neighbour (region) and OWN= own region. The figures in Panel A-C are estimated parameters. The numbers in the parentheses are *p*-values. * refers to significance at the 10 per cent level.

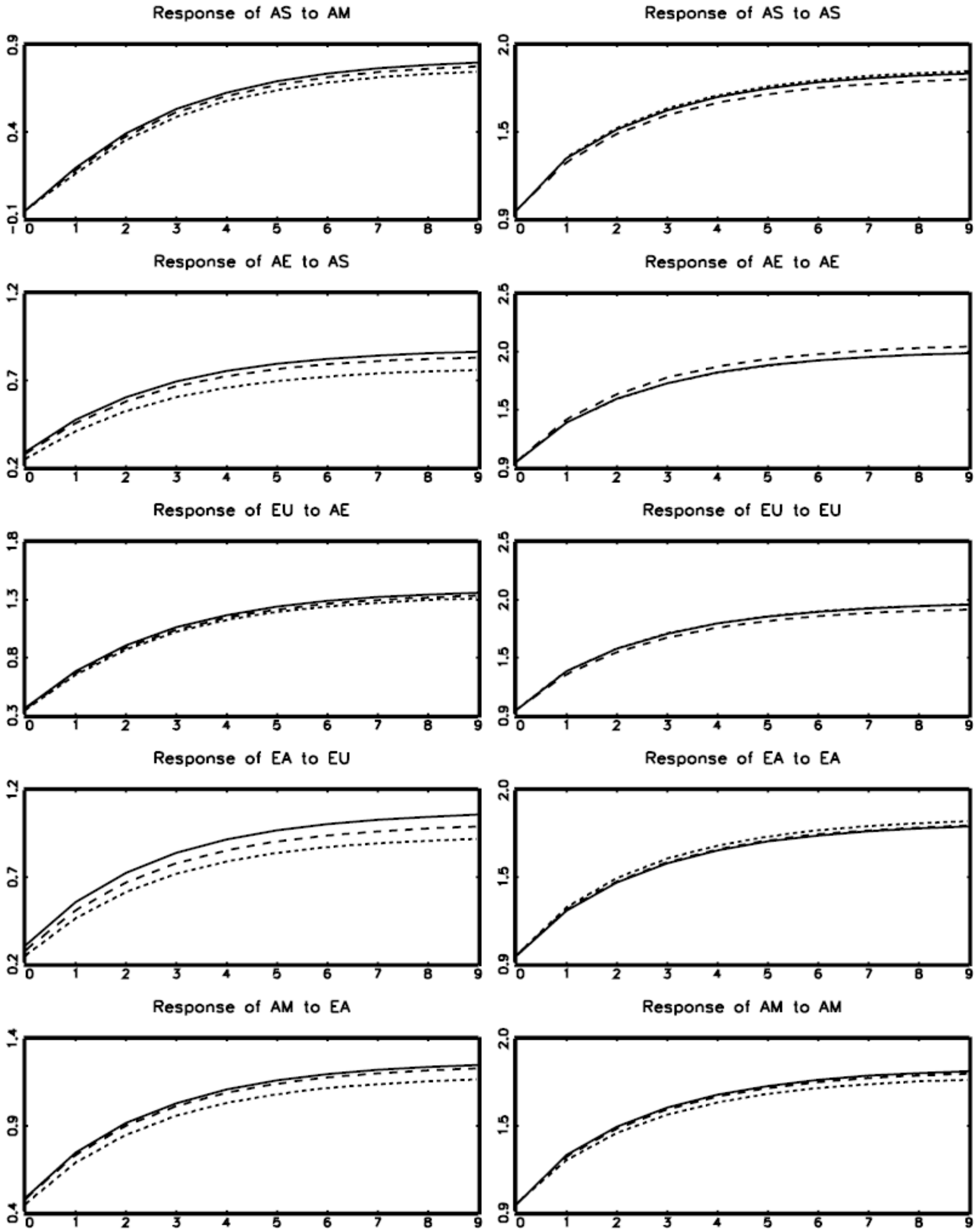
Table 9. Cumulative impulse response with the asymmetric effect model for Euro-US dollar volatility

Thresholds used for h_1 and h_2 are 30th and 70th percentiles

	Dependent region				
	AS	*AE*	*EU*	*EA*	*AM*
Panel A					
NN-High	0.94 (0.251)	1.12 (0.243)	1.57 (0.343)	0.95 (0.273)	1.11 (0.325)
NN-Neutral	0.97 (0.246)	1.05 (0.225)	1.55 (0.334)	1.03 (0.275)	1.16 (0.319)
NN-Low	0.91 (0.260)	1.04 (0.240)	1.60 (0.347)	1.00 (0.278)	1.22 (0.332)
Panel B					
OWN-previous-High	2.26 (0.318)	2.24 (0.328)	1.84 (0.258)	2.14 (0.303)	1.59 (0.193)
OWN-previous-Neutral	2.37 (0.325)	2.24 (0.326)	1.83 (0.253)	2.14 (0.300)	1.61 (0.193)
OWN-previous-Low	2.29 (0.333)	2.26 (0.333)	1.89 (0.266)	2.17 (0.306)	1.62 (0.201)

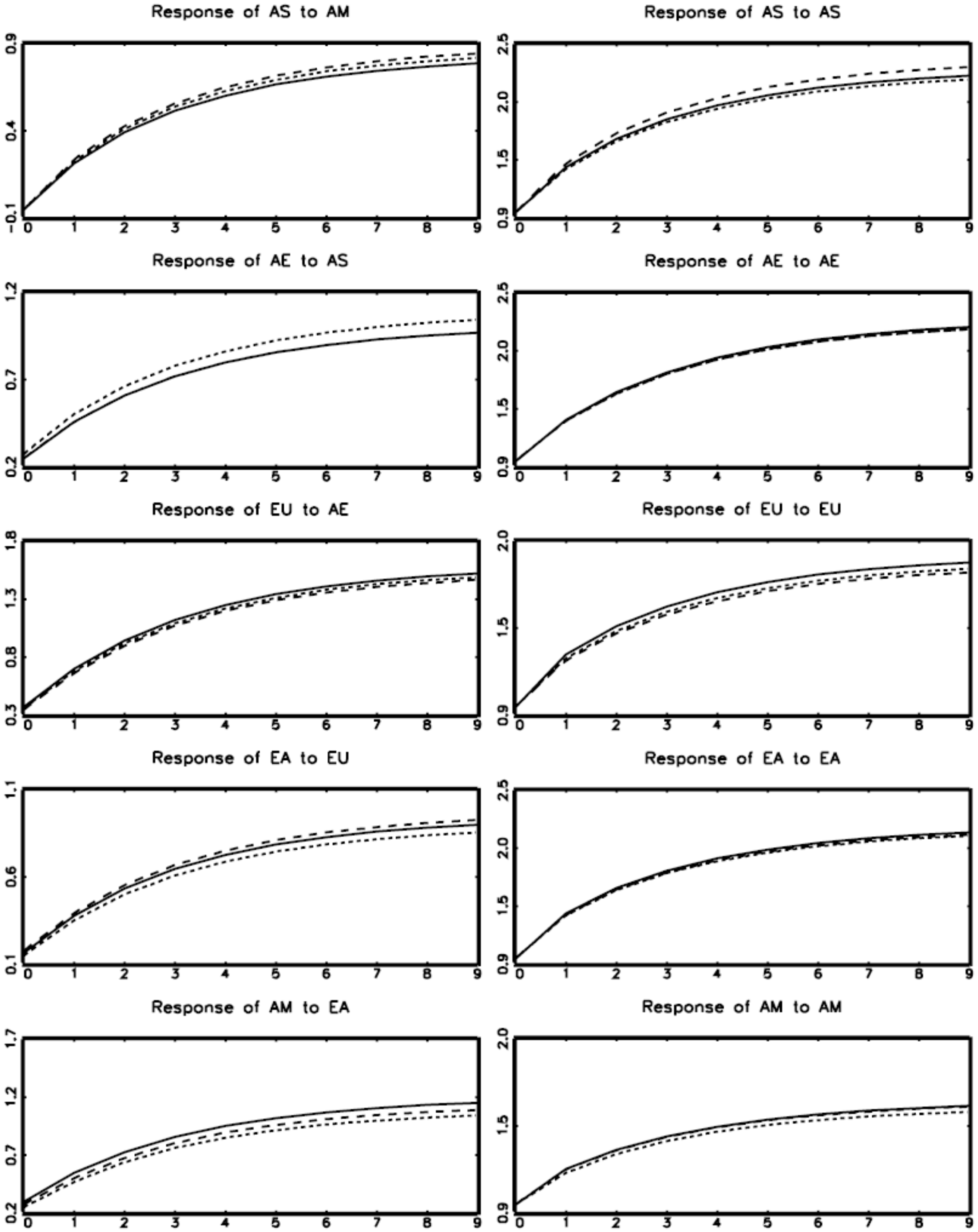
Notes: *AS* = Asia, *AE* = Asia and Europe overlap, *EU* = Europe, *EA* = Europe and America overlap and *AM* = America. The system of volatility equations estimated here is given in (7). To determine the thresholds h_1 and h_2 we consider the normalised daily exchange rate returns of all five regions over the full sample period. Then we set h_1 and h_2 as a percentile of the normalised returns. Cumulative response is the sum of first 200 period impulse responses. Impulse response is calculated with one unit shock in innovation in equation (7). Numbers in parenthesis are standard errors obtained with 1,000 residual bootstrap replications. In Panel A, we assume that each of the two cases, "High" and "Low", occurs once only at nearest neighbour and the other segments are fixed at "Neutral". In Panel B, we assume that each of the two cases, "High" and "Low", occurs once only in the own region in the previous day and the other regions are fixed at "Neutral".

Figure 1. Cumulative impulse response of volatility for US Dollar-Yen



Notes: The model used in the computation of cumulative response is given in (7). Short dashed, dashed and solid lines refer to cumulative impulse responses of "High", "Neutral" and "Low" cases, respectively. In the left five panels, we assume that each of the two cases, "High", "Low", occurs once only at the nearest neighbour and the other segments are fixed at "Neutral". In the right five panels, we assume that each of the two cases, "High", "Low", occurs once only in the own region in the previous day and the other regions are fixed at "Neutral".

Figure 2. Cumulative impulse response of volatility for Euro-US Dollar



Notes: The model used in the computation of cumulative response is given in (7). Short dashed, dashed and solid lines refer to cumulative impulse responses of "High", "Neutral" and "Low" cases, respectively. In the left five panels, we assume that each of the two cases, "High", "Low", occurs once only at the nearest neighbour and the other segments are fixed at "Neutral". In the right five panels, we assume that each of the two cases, "High", "Low", occurs once only in the own region in the previous day and the other regions are fixed at "Neutral".