Economic Modelling 61 (2017) 169–180

Contents lists available at ScienceDirect

Economic Modelling

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

Volatility spillovers and determinants of contagion: Exchange rate and equity markets during crises☆

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ARTICLE INFO

JEL Classification:
G12
G14

Keywords:
Volatility spillover
Contagion
Exchange rate market
Equity market
Financial crisis

ABSTRACT

We study the hourly volatility spillover between the equity markets of New York (DJI), London (FTSE 100) and Tokyo (N225) and their exchange rates (USD, EUR, GBP and JPY) for the period of 2001 through 2013 covering the non-crises period, the global financial crisis and the euro debt crisis. First, we find a general increase in spillover between the equity and exchange rate markets during the crisis periods. Second, pure contagion (attributable to irrational investors' behavior) and fundamental contagion (measured by macroeconomic fundamentals) explains the increased spillover between the FTSE 100, N225 to the DJI during the global financial crisis and from the exchange rate markets to the DJI during the euro debt crisis.

1. Introduction

A considerable body of evidence has been built upon the behavior and sources of financial asset return volatilities since the early studies of Baillie and Bollerslev (1991), and Lin et al. (1994). They show that volatilities vary across assets, asset classes, time periods and countries. This evidence has since been applied to different areas of finance including asset pricing, portfolio selection or market risk management.

International equity markets are highly integrated which may lead to high levels of cross-country investment flows as well as cross-market volatility interdependence (Bekaert and Harvey, 1995). Common research literature refers the seemingly unrelated cross-market volatility interdependence to volatility spillover effects. Since investors require foreign currencies to buy equity in international financial markets, exchange rate volatility can also influence the volatility of equity markets (Kanas, 2000).

In addition, the increasing periodicity of financial crises in recent years has given rise to considerable attention on the impact of crises on volatility spillover. Bekaert et al. (2005) and Bekaert et al. (2014) use the term "contagion" to describe the heightening of co-movements of markets as well as volatility spillover during crisis periods compared to non-crisis periods.

To explain contagion, the financial literature distinguishes between fundamental contagion and pure contagion. Dornbusch et al. (2000) provide evidence that contagion can be explained by economic fundamentals and use the term fundamental contagion. The idea of pure contagion has been alluded to in the seminal study by Lin et al. (1994), who attribute contagion to irrational investors' behavior which can lead to irrational phenomena like financial panics or herd behavior.

We apply a GARCH model to estimate the volatilities of the worldwide leading equity markets in the US, Europe and Asia in terms of market capitalization as well as turnover and of their corresponding exchange rates. In particular, we investigate the volatilities of the Dow Jones Index (DJI), FTSE 100 and Nikkei 225 (N225) and of the exchange rates between the currencies USD, EUR, GBP and JPY from 2001 to 2013. Furthermore, we use the estimated volatilities to study whether there is an increase in volatility spillover between the exchange rates markets and the equity markets during the global financial crisis and the euro debt crisis. Finally, we test whether fundamental contagion and pure contagion explain the increased spillover.

Previous research work like Coudert et al. (2011) focus on the volatility spillover effect in financial crises in general but do not examine their determinants. This study attempts to fulfill this research gap by investigating whether macroeconomic fundamentals like interest rates, trade balance and inflation or investors' behavior measured by liquidity as well as information asymmetry are influencing the

☆ The paper has been presented at the 2016 Applied Financial Modelling Conference, Deakin University, Melbourne, Australia. We thank Jonathan A. Batten; Niklas F. Wagner; Paresh K. Narayan; Zhuo Huang; and other conference participants for their insightful comments.
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http://dx.doi.org/10.1016/j.econmod.2016.12.011
Received 2 September 2016; Received in revised form 31 October 2016; Accepted 3 December 2016
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volatility spillover during financial crisis periods.

During the financial crisis periods, we observe positive volatility spillover between the DJI, the FTSE 100 and the N225. In the same period, we show significant volatility spillovers from the exchange rate markets to the equity markets. In particular, JPY based currencies reveal negative significant volatility spillovers against the DJI and FTSE 100. Finally, we find that the volatility spillover between the FTSE 100, N225 to the DJI during the global financial crisis is explained by inflation, a measure of fundamental contagion, and information asymmetry, a measure of pure contagion. Similarly, the volatility spillover changes from the exchange rate markets to the DJI during the euro debt crisis is due to fundamental factors including interest rates, trade balance and inflation as well as pure contagion measured by imperfect information and information asymmetry.

The remainder of the study is organized as follows. In Section 2, we review the literature of volatility spillover and develop our hypotheses. In Section 3, we describe our data sample and present descriptive statistics. In Section 4, we describe the methodology. In Section 5, we present the results of the volatility spillover during the financial crises and determinants of the contagion. We conclude in Section 6.

2. Literature review and hypotheses

2.1. Volatility spillovers across different financial markets

There are two main theoretical frameworks as seen from the firm's and the investors' view to explain volatility spillover between equity and exchange rate markets. Sercu and Vanhulle (1992) provides a possible reason for the linkages between exchange rates and stock markets from the firm's view. They break the stock market down into single firms which import and/or export goods and are consequently influenced by currency movements. Thus, the international competitiveness of firms, their real income as well as stock prices which are interpreted as the present value of the firms' future cash flows, are affected by exchange rates. As a consequence, there is a correlation between exchange rate and stock price volatility.

This theory of the correlation between exchange rate and stock price volatilities from the firm's view is also consistent with the theory from the investor's view. Karoui (2006) explains that investors who had already invested in stocks will seek other financial markets which may be more profitable if their local currency depreciates compared to the foreign currency. Thus, the correlation between exchange rates and stock prices will be negative. On the other hand, investors who have not yet invested will find the stocks cheap and buy them. Consequently, the effect leads to a positive correlation between exchange rates and stock prices. In sum, firms and investors' behavior drive the sign of the correlation of exchange rates and stock prices. Empirical evidence supporting the return and volatility spillover relation between financial markets are presented in Baele (2005) and Diebold and Yilmaz (2009). These studies examine the short-term relations among security prices across the three major markets Tokyo, London, and New York. Using an ARCH model, they reveal a significant correlation between the timing of mean as well as volatility spillovers amongst these markets.

Engle et al. (1990) apply a similar framework to exchange rate markets and examine two types of volatility spillovers which are known as heat waves and meteor showers. Their results provide evidence that the heat wave hypothesis has to be rejected and volatility exhibits not only country-specific autocorrelation. On the other hand, they document the dynamic effect of country specific news on the conditional volatility in the subsequent markets which validates the meteor shower hypothesis. This is in accordance with Baillie and Bollerslev (1991), who use hourly data on four major exchange rates to show that exchange rate volatility features similar patterns over different hours of the day and appears to be highly serially correlated. However, their findings also point out some heat waves, or market-specific news characteristics.[1]

Moreover, the volatility spillover effect between different types of asset markets within the same economy has been empirically examined. For example, Kansas (2000) investigates the connection of the conditional second moments between stock returns and exchange rate changes for the US, UK, Japan, Germany, France and Canada. He finds evidence of volatility spillover from stock returns to exchange rate changes for five of the six countries considered (except Germany). He also finds that the volatility spillovers are symmetrical surrounding releases of bad news and good news.

2.2. Volatility spillover changes in financial crises

Lin et al. (1994) show that markets around the world fall with surprising uniformity in financial crises. These cross-market connections often significantly increase after a shock to an individual country (or group of countries), as measured by the degree to which asset prices or financial flows move together across markets relative to this co-movement in tranquil times.

Dornbusch et al. (2000) shows that fundamental contagion such as macroeconomic shocks have repercussions on an international scale and local shocks transmitted through trade links, competitive devaluations, and financial links are possible channels for the spillover of crises between different markets. In contrast, pure contagion is related to liquidity problems, imperfect information and informational asymmetries and it has been shown that it leads to irrational phenomena like financial panics, herd behavior, loss of confidence and increased risk aversion of investors.

In the context of liquidity problems, Hernández and Valdés (2001) utilizes a model which combines illiquid countries with investors who potentially need liquidity in order to change their portfolio. If they do not find the liquidity in one country, then they will seek liquidity in a second country and this can cause volatility spillover. In addition, depositor panics or contractual links between banks, as well as bank failures, can shrink the common pool of liquidity, thereby creating or exacerbating aggregate liquidity shortages (Diamond and Rajan (2005)). As shown by Boyson et al. (2010), shocks to liquidity of hedge funds can also increase the probability of contagion.

This is in line with the theory of imperfect information in which a common information shock is taken as a basis and investors may believe that a financial shock in one country could lead to similar shocks in other countries whereby the trading activity and volatility in each market simultaneously increase (Fleming et al., 1998). Particularly, an information shock alters expectations in one market leading investors to adjust their holdings in other markets without taking account of changes in macroeconomic fundamentals. As a result of the existence of correlations between returns, portfolio rebalancing occurs because of the ensuing changes in hedging demand (Kallberg et al., 2005). It is also consistent with the model of Kodres and Pritsker (2002) in which contagion occurs through cross-market rebalancing due to investors' transmission of idiosyncratic shocks from one market to others by adjusting their portfolio exposures to shared macroeconomic risks. The model can generate contagion in the absence of news, as well as between markets that do not directly share macroeconomic risks and depends on the amount of information asymmetry in each market.

Calvo and Mendoza (2000) reconfirm the information asymmetry theory but they allege two different types of investors: those who gather the relevant information, and those who just follow the crowd. Under this market-contagion scenario, speculative trading and noise trading (in the sense of Black (1986), De Long et al. (1990) or Kyle and Xiong (2001)) may occur in the international context. Thus, price movements driven by fads and a herd instinct may be transmittable across borders

[1] For further studies see Hong (2001) and Melvin and Melvin (2003).

(Lin et al. (1994)).

Empirical evidence of contagion is provided by Diebold and Yilmaz (2009). They conclude that volatility spillovers between equity markets may be observed during financial crises. Kansas (2000) confirms that volatility spillovers from stock returns spillovers to exchange rates have increased since the October 1987 crash but he did not examine if this trend is fundamentally driven or caused by other determinants. Choi et al. (2009) conduct a similar study with the data of the New Zealand (NZ) stock and exchange rate market. They find significant volatility spillovers from exchange rate movements to stock returns in NZ for the periods before and after the 1997 crash.

2.3. Hypotheses

We examine the impact of financial crises on volatility spillover between the exchange rate market and the equities market on an hourly basis. In accordance with prior studies such as Lin et al. (1994), we predict an increase in volatility spillover between the global equity markets during the global financial crisis and the euro crisis. Furthermore, we expect that volatility spillover between stock markets as well as between equity markets and exchange rates are significantly higher during the two crises.

Finally, we attempt to fulfill the research gap by investigating the theoretical framework of “fundamental-based contagion” such as interest rates, trade balance and inflation and “pure contagion” such as liquidity and information asymmetry in the context of financial crises. We expect both types of contagions to underlie exchange rate-equity market volatility spillovers as well as inter-equity market volatility spillovers.

3. Data and preliminary testing

3.1. Data of equity markets

In this study we use the equity market indices DJI of the New York Stock Exchange (NYSE), FTSE 100 of the London Stock Exchange (LSE) and N225 of the Tokyo Stock Exchange (TSE). The three data samples include hourly prices for the period 01/01/2001 to 26/04/2013 provided by Thomson Reuters tick history and are adjusted for dividends. We calculate the returns of the stock indices as the difference between the natural logarithms of the prices between subsequent hours. We carry out analyses on an hourly basis (compared to daily intervals employed in Kanas, 2000) because we expect that volatility is transmitted almost instantaneously given the high degree of connectivity between the major financial markets around the globe in the past decade.

Table 1 presents the descriptive statistics and preliminary results of our data sample, which consists of 21,498 observations from the DJI, 35,940 observations from the FTSE 100 and 18,366 observations of the N225. The TSE opens from 01.00–3.30 a.m. to 04.30–07.00 a.m., the LSE from 09.00 a.m. to 5.30 p.m. and the NYSE from 2.30 p.m. to 9 p.m. (all GMT).

Table 1 shows similar sample means for all stock indices. The variance of the N225 is approximately two times the variance of the other two stock indices. Moreover, the empirical distributions of FTSE 100 and N225 are negatively skewed whereas the distribution of DJI is positively skewed. All three stock indices are highly leptokurtic compared to the normal distribution. The deviation compared with the normal distribution is confirmed by the Jarque-Bera-Test. The Ljung-Box-Test shows significant serial autocorrelation for stock index returns as well as squared returns and the Augmented Dickey-Fuller-Test points to stationarity in the return series.

These results are consistent with Kansas (2000) and indicate significant linear and nonlinear dependencies which may be captured by autoregressive conditional heteroscedasticity (ARCH) models.

Table 1
Descriptive and preliminary data analysis for stock index returns (in %). Table 1 illustrates the descriptive and preliminary test results of the stock index returns. We use a Jarque-Bera-Test to examine the normal distribution of our data sample. Ljung and Box (1978) test is applied to examine autocorrelation of the stock index returns as well as the squared returns. Furthermore, the Augmented Dickey-Fuller-Test (1979) is used to check the return time series for unit roots (Dickey and Fuller, 1979).

Statistic	DJI	FTSE 100	N225
N	21,498	35,940	18,366
Sample Mean	0.001	< 0.001	< -0.001
Median	0.006	0.002	-0.001
Variance	0.193	0.133	0.297
Skewness	0.064	-0.349	-0.166
Kurtosis	16.05	25.66	12.93
Jarque-Bera	230,625***	986,119***	127,867***
LB(24)	228.77***	135.25***	445.55***
LB^2(24)	9999***	8569***	8406***
ADF (20)	-31.25***	-43.15***	-30.71***

Note: *Statistically significant at the 10% level. **Statistically significant at the 5% level. *** Statistically significant at the 1% level.

3.2. Data of exchange rate markets

We examine the volatility spillovers of exchange rates with a base currency which corresponds to the denomination of the equity market index from 01/01/2001 to 26/04/2013. Namely, the USD/EUR, USD/JPY, and USD/GBP to the DJI; the GBP/USD, GBP/EUR, and GBP/JPY to the FTSE 100; and, the JPY/USD, JPY/EUR, and JPY/GBP to the N225. Data is sourced from the Thomson Reuters tick history database. Hourly exchange rates are matched to their corresponding equity market index using GMT trade times as the baseline. The hourly volatilities and the hourly returns (difference between the natural logarithms of the exchange rates between successive hours) are computed.

Table 2 shows that all exchange rate returns exhibit small means and medians for the whole sample from 2011 to 2013. On the other hand, the variance of all exchange rate returns except JPY/EUR and USD/JPY is high which may be indicative of the high outliers and high volatilities during the financial crisis periods. The skewness and kurtosis indicate a deviation compared to the normal distribution which is confirmed by the significant results of the Jarque-Bera-Test.

Using the same preliminary tests previously applied to the stock market indices, we provide evidence that all exchange rate returns are serial auto-correlated and stationary. As such, we apply the autoregressive conditional heteroscedasticity (ARCH) models to calculate their volatilities.

3.3. Indicators, macroeconomic fundamentals and contagion proxies

Further, we utilize indicators for the financial crises, macroeconomic fundamentals and market microstructures measures to analyze the contagion effect. The data runs from 01/01/2002 to 26/04/2013 on a monthly basis.

As an indicator for the global financial crisis we choose the TED-Spread which is the difference between the 3-month LIBOR and the 3-month treasury bill. The data for the 3-month treasury bill is downloaded from the Federal Reserve[2] and the data of the 3-month LIBOR is offered by the British Bankers' Association.[3] We also use the data of the S & P/Case-Shiller Home Price Index as an indicator for the global financial crisis.[4]

To measure the impact of the euro crisis we calculate the abnormal

[2] http://www.federalreserve.gov/releases/h15/data.htm
[3] http://research.stlouisfed.org/fred2/series/USD3MTD156N
[4] http://www.spindices.com/index-family/real-estate/sp-case-shiller

Table 2
Descriptive and preliminary data analysis for exchange rate returns (in %). Table 2 illustrates the descriptive and preliminary data analysis for our exchange rate returns. The same preliminary tests as used for the stock index returns are applied for the exchange rate returns.

Statistics	USD/EUR	USD/GBP	USD/JPY	GBP/EUR	GBP/JPY	JPY/EUR
Sample Mean	< -0.001	< 0.001	< -0.001	< 0.001	< -0.001	< 0.001
Median	0.01	0.02	0.001	0.004	0.01	0.01
Variance	6.22	6.48	0.357	3.41	8.29	0.028
Skewness	0.039	0.153	0.039	56.91	0.103	0.876
Kurtosis	4461	42,042	12,949	21,751	21,691	43.31
Jarque-Bera	$>1\times10^{6***}$	$>1\times10^{6***}$	$>1\times10^{6***}$	$>1\times10^{6***}$	$>1\times10^{6***}$	$>1\times10^{6***}$
LB(24)	9999***	9999***	9999***	9999***	9999***	82.98***
LB^2(24)	9999***	9999***	9999***	9999***	9999***	4851***
ADF (20)	-107.53***	-107.87***	-81.05***	-100.69***	-99.52***	-63.59***

Note: GBP/USD, JPY/USD, JPY/GBP have the different sign of sample mean and skewness. *Statistically significant at the 10% level. ** Statistically significant at the 5% level. *** Statistically significant at the 1% level.

euro yields by subtracting the US 10-Year Treasury Note yields[5] from the euro bond yields provided by the European Central Bank.[6] The Centre for European Economic Research (ZEW) indicator for economic sentiment is used as an instrument variable for the abnormal euro yields in our examination.[7]

By using the monthly data of the US inflation, the trade-balance between the US and all other countries and the US interest rate measured by US 10-Year Treasury Note yields as fundamental numbers of the US we can control our examination for macroeconomic shocks on the equity market. This fundamental data is available at the Federal Reserve Bank of St. Louis.[8]

Finally, we test for irrational investors' behavior in financial crises which can be measured by the liquidity of a market and the existing informational asymmetries. Therefore, we apply the volume of block trades to the total trading volume. The data is provided by Thomson Reuters tick history.

4. Methodology

4.1. Calculating hourly volatilities

As already examined by Mandelbrot (1963) and Fama (1970) exchange rates exhibit volatility clustering so that "large changes tend to be followed by large changes - of either sign – and small changes tend to be followed by small changes". In further studies, Engle (1982), Domowitz and Hakkio (1985) and McCurdy and Morgan (1988) have shown that the changes of many financial time series tend to be serially correlated and they could document the forecastability of volatility.

For this reason, the dynamic process of hourly volatilities is formulated by the following GARCH (Generalized Autoregressive Conditional Heteroskedastic) model introduced by Bollerslev (1986):

$$\varepsilon_{i,t}|\vartheta_{i,t-1}\sim N(0,h_{i,t})\text{ for i = } 1, 2, \ldots, n \tag{1}$$

$$\sigma_{i,t}^2 = \alpha_0+\sum_{j=1}^{q}\alpha_j\varepsilon_{i,t-j}^2+\sum_{j=1}^{p}\beta_i\sigma_{i,t-j}^2 \tag{2}$$

In this model $\varepsilon_{i,t}$ denotes the innovations in a linear model, $\vartheta_{i,t-1}$ the previous information and $\sigma_{i,t}^2$ the conditional variance. The model allows the conditional variance of a financial time series to change over time as a function of past errors as well as the past conditional variances.

The GARCH regression model is written as:

$$\varepsilon_t = y_t-x_t'*b \tag{3}$$

y_t is the dependent variable, x_t' is a vector of explanatory variables and b is a vector of unknown parameters in this regression equation. Subsequently, a log likelihood function $L_{i,t}(\theta)$ for a sample of T observations is considered and an iterative procedure is used to obtain maximum likelihood estimates and second-order efficiency:

$$L_{i,t}(\theta) = T^{-1}*\sum_{t=1}^{T}-\frac{1}{2}\log(\sigma_{i,t})-\frac{1}{2}\varepsilon_{i,t}^2\sigma_{i,t}^{-1} \tag{4}$$

An iterative procedure described in Bollerslev (1986) is used to obtain maximum likelihood estimates and second-order efficiency.

In this paper we use a GARCH (1,1) model to estimate the GARCH coefficients for all equity markets and exchange rates. Based on these coefficients, the hourly conditional variances are calculated with the initial values for $h_{i,t}$ and $\varepsilon_{i,t}$ for the period from 2001 to 2013.

4.2. Volatility spillover between different markets

4.2.1. General volatility spillover effects

To analyze the spillover effects between the estimated GARCH volatilities of equity markets and exchange rates to equity markets, we apply a linear regression framework for the whole period from 2001 to 2013 similar to Coudert et al. (2011). The regression model can be expressed as below with n denoting the number of explaining exchange rates, $\sigma_{EQ,i}^2$ denoting the volatility of an equity market and $\sigma_{EX/EQ,k}^2$ denoting the volatility of the remaining equity markets or corresponding exchange rate markets. The volatilities of the remaining equity markets or corresponding exchange rate markets $\sigma_{EX/EQ,k}^2$ represent the independent variable for the analysis of spillover effects between equity markets.

$$\sigma_{EQ,i}^2 = \alpha_{i,0}+\sum_{k=0}^{n}\alpha_{i,k}\sigma_{EX/EQ,k}^2+\varepsilon_{i,k} \tag{5}$$

The spillover coefficient $\alpha_{i,k}$ examines whether the volatility of the remaining equity markets or the exchange rates affect the volatility of the equity markets. To assess if there is a volatility spillover effect between the exchange rates and the equity markets, we also control for exchange rate volatilities which are not noted against the respective currency of the considered equity market.

By using a *t*-test we test if the estimated coefficients are significantly different from zero. We adjust the standard errors by applying a Newey-West method with three lags to handle the existence of autocorrelation of volatilities as presented in the seminal work of Mandelbrot (1963). To check for multicollinearity, we also calculate the tolerance, VIF and the condition index of the independent variables. It is not necessary to use additional non-parametric tests to handle the deviation from the normal distribution (shown in Tables 1 and 2) due to the high sample size.

4.2.2. Volatility spillover effects in financial crises (Contagion)

Several studies like Dungey and Zhumabekova (2001) have shown

[5] http://research.stlouisfed.org/fred2/categories/22
[6] http://www.ecb.int/stats/money/yc/html/index.en.html
[7] http://www.zew.de/
[8] http://research.stlouisfed.org/fred2/categories/22

that spillover effects are significantly affected by the extent of “crisis” periods. Unfortunately, many popular models produce insufficient results when fit to the data. To deal with this issue, Baele (2005) applies Markov Regime-Switching models in order to distinguish between periods of high and low spillover intensity, as well as high and low volatility. As outlined by Coudert et al. (2011) it is also appropriate to apply threshold models such as a smooth transition regression or an extremal dependence measure.

However, many further studies have noted the inability of threshold or regime switching models to generate superior out-of-sample forecasting accuracy than linear models in spite of their apparent ability to fit the data better in a sample. A possible argument provided by Dacco and Satchell (1999) suggests that regime switching or threshold models may forecast poorly due to the difficulty of forecasting the regime that the series will be in.

As a consequence of this we choose the straightforward framework of individual linear regressions in subsamples and add dummy variables to examine possible changes of volatility spillover effects in financial crises. Furthermore, the current regime is usually directly observable in financial crises as it is outlined in the figures of volatility over time.

The examination of volatility spillover effects in financial crises in our paper is structured in the following way:

First, we determine the starting and ending point of the financial crises included in our complete sample with the aid of characterizing events of financial crises. These periods of financial crises provide the frame for respective subsamples. The remaining periods build the subsamples of non-financial crises.

Based on the different subsamples we apply a Chow-Test to investigate if the different non-financial crisis and financial crisis periods are characterized by structural breaks in the time series. Thereby, we can statistically answer the question whether two sets of observations can be regarded as belonging to the same regression model or whether different subsamples with individual regression models fit the data better.

The Chow-Test statistic equals:

$$T = \frac{(S-(S_a + S_b)/(k+1)}{(S_a + S_b)/(N_a + N_b - 2(k+1)} \tag{6}$$

In this test statistic S denotes the sum of squared residuals (SSR) and S_a as well as S_b equal the sum of squared residuals of the different subsamples. We perform the Chow test between each sequenced combination of subsamples. Thereby, we can justify the choice of the subsamples and the use of individual regression models for the different periods.

After selecting the different subsamples, we apply the same linear regression framework as for the whole sample. To test for significant differences between the financial crisis subsamples, we also run a linear regression model with the data of both subsamples. In this regression model we add variables consisting of a dummy variable (zero for euro crisis and one for GFC) multiplied by the examined exchange rate or equity market volatilities. The auxiliary regression model to test for significant different variables in two subsamples is stated below:

$$\sigma^2_{EQ,i} = \alpha_{i,0} + \sum_{k=0}^{n} \alpha_{i,k}\sigma^2_{EX/EQ,k} + dummy\_fc*\sigma^2_{EX/EQ,k} + \varepsilon_{i,k} \text{ With } dummy\_fc = \begin{cases} 0 & for\ GFC \\ 1 & for\ reurocrisis \end{cases} \tag{7}$$

A statistically significant interference variable between the dummy variable and one of the exchange rate or equity market volatilities points towards a change in volatility spillover between the financial crises.

4.3. Determinants of Contagion

4.3.1. Applying indicators to determine financial crises

We test the robustness of our results at the subsample level by extending our basic regression model with financial crises indicators. The advantage of indicators compared to subsamples is that the size of the sample persists and characterizing starting and ending dates of the subsamples do not have to be chosen. Instead the indicator is a consistent measure which increases in financial crises.

To indicate the period of the global financial crisis we select the TED-spread which is the difference between the 3-month LIBOR and the 3-month Treasury Bill. It expresses the credit risk in the financial system or the unwillingness of banks giving loans. This indicator shows clear jumps particularly during the global financial crisis when the majority of banks were facing out liquidity issues. We also use the S & P/Case-Shiller Home Price Index as an indicator for the global financial crisis considering that the crisis was triggered by the US house market.

In addition, we select the euro bond yields adjusted by US 10-year t-note yields as an indicator for the euro crisis. The bond yields of several European countries rose dramatically in this period and indicate the peaks of the crisis closely. Finally, we use the ZEW indicator which presents the economic sentiment of Germany. Since the German economy strongly depends on the export to other European countries the ZEW indicator shows clear spikes during the euro crisis.

Nevertheless, these indicators could potentially be endogenous. As such, we apply the Durbin-Wu-Hausmann test to reveal any possible endogeneity.

4.3.2. Proxies controlling for fundamental contagion

We expand the linear regression model of Eq. (6) using the crisis indicators to examine whether volatility spillover changes are attributable to the following macroeconomic factors:

4.3.2.1. Trade-Balance. As outlined by Dornbusch et al. (2000) markets in different economies are combined by their trade links. Particularly with regard to volatility spillover, trade links could act as the respective macroeconomic transmission channel. Trade balance can be measured by the balance of imports and exports to a single economy or amongst all other trading partners. Furthermore, the trade balance of an economy affects the exchange rate between the domestic currency and the currency of the trading partner. With respect to financial crises, any major trading partner of a country in which a financial crisis has induced a sharp currency depreciation could experience declining asset prices and large capital outflows.

In this study we analyze whether volatility of one market is the main influencing factor of the volatility of another market by controlling for their trade balance. By expanding our model by the trade balance we can also examine if possible volatility spillover changes in financial crises are fundamental-based or if they belong to investors' behavior.

4.3.2.2. Inflation. In the study of Schwert (1989) the author shows that stock market volatility changes through time and that this changes are related to a variety of economic variables. One of these influencing factors could be the volatility of inflation.

4.3.2.3. Interest rates. Lauterbach (1989) shows that macroeconomic volatility is related to interest rates. To verify if volatility spillover is driven by macroeconomic fundamentals, we control for the level of interest rates in our model using the 10-year US Treasury Note.

4.3.3. Proxies controlling for pure contagion

After controlling for macroeconomic fundamentals, we also examine whether volatility spillover changes in a financial crisis is driven by "pure contagion". As Dornbusch et al. (2000) show, contagion could belong to irrational investors' behavior which is related to liquidity problems as well as asymmetrical and imperfect information. To measure these three contagion triggers we use the following proxies:

4.3.3.1. Trading volume. Aitken and Comerton-Forde (2003) find evidence that trade-based measures can be used to proxy for liquidity in a market. In our model we use the logarithm of the trading volume of all included stocks to determine capital in- and outflows in financial crises to control for "pure contagion".

Additionally, the trading volume can also be applied to detect herding in financial markets. In this context, Lakonishok et al. (1992) and Wermers (1995) examine the tendency of individuals or certain groups of investors to follow each other and trade an asset at the same time.

4.3.3.2. Block volume. As illustrated by Holthausen et al. (1987), the sale (purchase) of a large block suggests that the seller (buyer) believes that the stock is overvalued or undervalued. The argument is that the seller (buyer) of large blocks is more likely to possess private information due to its identity (often directors of companies). Therefore, we use the block volume of a market in relation to the normal trading volume as a proxy for informational asymmetries in a market.

4.3.3.3. Pricing error variance. The last proxy used in our model is the pricing error variance which can indicate the market efficiency of processing information. Hasbrouck (1993) shows that the pricing error is the difference between the efficient price and the actual transaction price and that it consists of an information-correlated part $\alpha * w_t$ and an information-uncorrelated part n_t. So the pricing error can be calculated by the following formula:

$$s_t = \alpha * w_t + n_t \tag{8}$$

He demonstrates that the information-uncorrelated pricing errors are likely to result from price discreteness, transient liquidity effects, inventory control effects and "noise" trading. On the other hand, information-correlated pricing errors arise from adverse-selection effects in the presence of fixed transaction costs and from lagged adjustment to information. In our model we use Beveridge and Nelson (1981) decomposition, which assumes that the pricing error is entirely information-correlated, to calculate the price error variance.

5. Empirical results

5.1. Estimated volatilities of stock index and exchange rate returns

The results for the estimated GARCH (1,1) coefficients of the three stock indices DJI, FTSE and N225 and the six different exchange rates are shown in Table 3.[9] Except for USD/EUR and USD/GBP, every volatility time series exhibit significantly high intraday periodicity and persistence showing volatility clustering on an hourly basis, consistent with Andersen and Bollerslev (1997).

In the next step, we analyze all volatilities except USD/GBP based on the calculated GARCH (1,1) models over time. Due to the low coefficient of USD/GBP, we analyze the realized volatilities of USD/GBP instead.

Table 3
Estimated GARCH (1,1) coefficients. Table 3 presents the estimated GARCH(1,1) coefficients of the stock indices and the exchange rates. The GARCH (1,1) model provides a representation of the leptokurtosis and time-dependent conditional heteroskedasticity of the examined return series (Baillie and Bollerslev (2002)).

Variable	GARCH(1,1) coefficient	Variable	GARCH(1,1) coefficient
StockIndices:		**Exchange Rates:**	
DJI	0.977***	**USD/EUR**	0.191***
		USD/GBP	0.002
		USD/JPY	0.317***
FTSE	0.980***	**GBP/EUR**	0.979***
		GBP/JPY	0.922***
N225	0.972***	**JPY/EUR**	0.965***

Note: GBP/USD, JPY/USD, JPY/GBP have the same GARCH(1,1) coefficient as their opposing exchange rates.* Statistically significant at the 10% level.** Statistically significant at the 5% level.*** Statistically significant at the 1% level.

Fig. 1 presents the calculated volatilities for the stock indices of DJI, FTSE 100 and N225. It indicates a similar volatility pattern for the three equity markets. In particular, all three markets exhibit relatively high volatility peaks in the global financial crisis of 2008/2009. The euro crisis beginning in 2010 is shown to primarily influence the volatilities of the DJI and FTSE 100 but less so for the N225. The results suggest that the two financial crises may be related to large volatility spillovers between the three equity markets. In the global financial crisis, an increase in volatility spillover between the equity markets appears to be the highest. On the other hand, a volatility spillover increase in the euro crisis is only observed between the DJI and FTSE.

This is in line with Baele (2005) who provides evidence for contagion effects from the US market to a number of European markets in times of high equity market volatility. Diebold and Yilmaz (2009) also confirm these results with the aid of a volatility spillover index by showing that volatility spillover between 19 equity markets display clear spikes during crisis events.

We also examine the volatilities of the exchange rate series calculated by GARCH (1,1) models. Fig. 2 shows relatively high volatility peaks for the exchange rates during the global financial crisis 2007 and mid-2009. Specifically, the volatilities of GBP/JPY, USD/EUR and USD/GBP show high peaks during the global financial crisis which substantiate the high average variances among the different

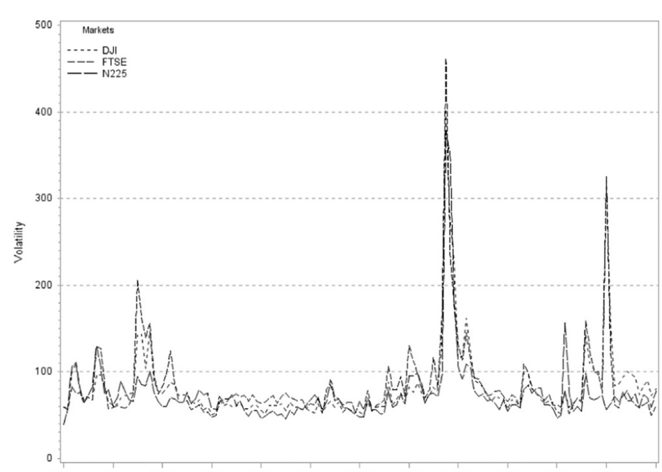

Fig. 1. Volatilities of DJI, FTSE and N225 Returns over Time, This figure depicts the volatilities calculated by a GARCH (1,1) model of DJI, FTSE 100 and N225 from 2001 to 2013. Using the calculated GARCH (1,1) volatilities ensure the representation of volatility clustering especially concerning abnormal peaks in the financial crises.

[9] The ARCH coefficients of the GARCH model have been calculated and used for estimating the volatilities as well, but they are excluded in Table 3 for brevity.

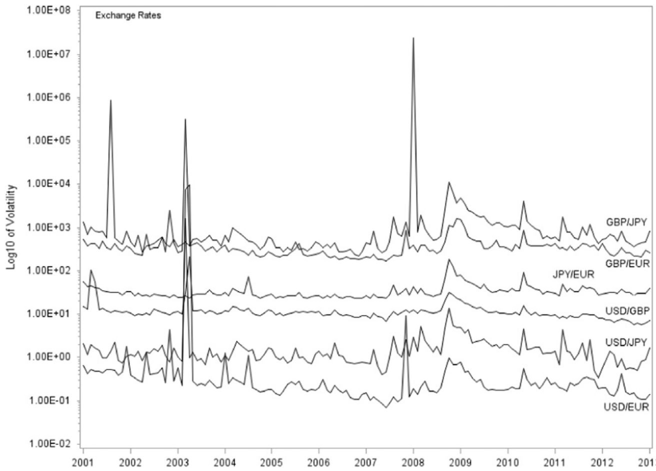

Fig. 2. Volatilities of Exchange Rate Returns over time, This figure demonstrates the exchange rate volatilities calculated by GARCH(1,1) models except the volatility of USD/GBP which is calculated using realized volatility. The exchange rate volatilities over time shown in the figure are arranged according to the sequence of exchange rates shown in the legend. Note: GBP/USD, JPY/USD, JPY/GBP have the same volatility run as their opposing exchange rates.

exchange rates over the whole sample (see Table 2 variance values, GBP/JPY=8.29, USD/EUR=6.22 and USD/GBP=6.48). In the euro crisis beginning in 2010, intensified spiking is observed for all exchange rate volatilities until the beginning of 2012. These results are consistent with Coudert et al. (2011), who show that major crises can trigger a surge in the currency volatility of markets.

Fig. 2 also refers to a similar pattern of our volatilities of exchange rates over time and points to a possible volatility spillover between exchange rates to the equity markets. In the end of 2008 when the three main equity indices exhibit their highest volatilities, each exchange rate volatility shows the same pattern. A similar spillover effect can be detected in the beginning of the euro crisis in 2010. At this time both equity markets and exchange rate volatilities show clear spikes.

5.2. General volatility spillover effects

Figs. 1 and 2 point towards possible volatility spillovers between the equity markets as well as between the equity markets and their underlying exchange rates. Table 4 shows the results of the tests for hourly volatility spillover effects using a linear regression model for the complete data sample. For each regression, we control for the exchange rate which is not directly linked to an equity market to ensure that none of our independent variables exhibit spurious correlation (R^2 increases after adding the control variable). For instance, in Table 4 Panel B, the regression on DJI includes a control for GBPEUR and the N225 includes a control for USDEUR.

In Table 4 Panel A we provide evidence that in the period of 2001–2013 all equity markets, except between FTSE 100 and N225, reveal significant volatility spillover in general. This is consistent with Lin et al. (1994) and confirms the meteor shower effect investigated by Engle et al. (1990). It shows that the volatility at the opening hour of a market is influenced by the closing or overlapping (if the equity market with the earlier opening time is still open) volatility of equity markets with an earlier opening time. For example, the volatility of FTSE 100 at 2 p.m. (not at the closing hour) is used to examine a spillover effect on the volatility of DJI at the beginning hour at 2 p.m. In Table 4, this overlapping effect is examined by the variable FTSE_Overlap. Any residuals of the regressions may possibly represent country-specific information which contributes to the volatility of an equity market as suggested by Ross (1989).

Table 4 Panel B demonstrates that the exchange rate volatilities have a positive significant impact on the DJI volatility in the period of 2001–2013. It also shows that the volatility of the exchange rates is transmitted within one hour except for the significant hour lagged volatility of USD/EUR (VOL_EUR(LAG)). Furthermore, a significant hourly volatility spillover exists between the FTSE 100 and all corresponding exchange rates (VOL_EUR, VOL_JPY and VOL_USD). However, the volatility of exchange rates represents only a small proportion of the volatility of FTSE indicated by the small R^2. Thus, other factors, such as the arrival of news as suggested by Engle and Ng (1993), may possibly play a role in the volatility of the FTSE 100. Finally, we find evidence that the volatility of JPY/EUR, JPY/GBP and the control variable USD/EUR are transmitted to the N225 within the hour. In contrast, we do not find evidence of volatility spillover from JPY/USD to N225.

The significant volatility spillovers between exchange rates and equity markets are in line with Sercu and Vanhulle (1992), who argue that currency movements influence the international competitiveness of firm, their real income and in turn stock price movements.

5.3. Volatility spillover effects in financial crises (Contagion)

We now examine the volatility spillover effects during financial crises. Figs. 1 and 2 provide a visual examination of the possible structural breaks in the volatility time series of exchange rates and equity markets. We apply the Chow test to confirm the period of the financial crises. The global financial crisis (GFC) contains the period from 02/04/2007 to 06/01/2009 and the euro crisis (EURO) contains the period from 20/10/2010 to 26/04/2013. The remaining periods between 2002 and 2013 are called non-financial crisis 1 (NFC1) and non-financial-crisis 2 (NFC2).

Table 5 presents the results of the Chow Test and confirms structural breaks between the non-financial crises and the financial crises occur (except GBP/JPY at the ending of the GFC) and confirm the volatility patterns found in Figs. 1 and 2. Based on these defined periods, we apply our regression framework to the subsamples of the GFC and EURO.

Table 6 results show that significant volatility spillovers occur between FTSE 100 and N225 to DJI in both the GFC and the euro crisis. We demonstrate that the volatility spillover from FTSE 100 to DJI is significantly higher in the euro crisis than in the GFC and that the volatility spillover of N225 to DJI is significantly lower in the euro crisis than in the GFC.

Additionally, we find evidence for significant volatility spillovers from DJI and N225 to FTSE 100 in both the GFC and the euro crisis. Moreover, both volatility spillovers from DJI and N225 to FTSE 100 are significantly higher in the GFC than in the euro crisis. Finally, we find significant volatility spillover from DJI to N225 in the GFC.

Thus, the FTSE 100 (FTSE(Overlap)) is the only source of a higher volatility spillover in the euro crisis in comparison to the GFC, suggesting that the locality of the exchange, being in the Eurozone, may have played a role in influencing the significance of volatility spillovers. On the other hand, the DJI and N225 coefficients have shown to contribute to a greater volatility spillover during the GFC relative to the euro crisis.

Our results are partially in contrast to those presented in Lin et al. (1994) who show that markets around the world fall with surprising uniformity in financial crises.

Table 7 shows the volatility spillovers between the exchange rates to the equity markets in the GFC and the euro crisis. For the DJI, we find significant volatility spillovers from the exchange rates during the GFC and the euro crisis. The USD/JPY (Vol_JPY) reveals a significantly negative volatility spillover and both the USD/EUR and USD/GBP exhibit significant positive volatility spillovers. Additionally, all exchange rates show a greater volatility spillover during the GFC as opposed to the euro crisis.

Similar results are obtained for the volatility spillover between the exchange rates and the FTSE 100. All exchange rate volatilities reveal a

Table 4
Volatility spillover over the complete sample. Panel A of Table 4 shows the results of volatility spillover between equity markets andala5 panel B indicates possible volatility spillover between exchange rates to equity markets. Due to the autocorrelation of volatilities shown in Tables 1–3, we adjust the standard errors by applying a Newey-West method with three lags. In order to check against spurious correlations, we also control our regression for main exchange rates which are not directly linked to an equity market. We also inspect for multicollinearity by calculating the tolerance, VIF and condition index of the independent variables. $\sigma^2_{EQ,i}=\alpha_{i,0}+\sum_{k=1}^{n}\alpha_{i,k}\sigma^2_{EX/EQ,k}+\varepsilon_{i,k}$

Variable	Estimate	t Value	Tolerance / VIF	Condition Index	Variable	Estimate	t Value	Tolerance / VIF	Condition Index	Variable	Estimate	t Value	Variable	Estimate	t Value	Tolerance / VIF	Condition Index
	Panel A: Volatility Spillover between Equity Markets																
DJI					**FTSE 1**					**FTSE 2**				**N225**			
Intercept	0.055***	2.87			**Intercept**	0.160***	8.31			**Intercept**	0.036***	3.17	**Intercept**	0.046	1.01		
Ftse_Overlap	0.779***	10.82	0.428 / 2.338	1.000	**N225_Close**	0.348***	8.91	–	–	**DJI_Overlap**	0.624***	25.22	**DJI_Close**	1.230***	6.66	0.183 / 5.459	1.000
N225_Close	0.326***	7.61	0.428 / 2.338	2.686									**FTSE_Close**	-0.215	-1.17	0.183 / 5.459	4.448
NOBS	2990				**NOBS**	3570				**NOBS**	25961		**NOBS**	1600			
Adj. R^2	0.862				**Adj. R^2**	0.492				**Adj. R^2**	0.591		**Adj. R^2**	0.733			
	Panel B: Volatility Spillover between Exchange Rates and Equity Markets																
	DJI				**FTSE**									**N225**			
Intercept	0.29***	23.08			**Intercept**	0.34***	236.56						**Intercept**	0.34***	5.34		
Vol_Eur (LAG)	48.00***	4.41	0.759 / 1.318	1.000	**Vol_Eur**	> 0.001***	3.38	1.000 / 1.000	1.000				**Vol_Eur**	4.21***	3.72	0.962 / 1.039	1.000
Vol_Jpy	1.92***	2.99	0.853 / 1.172	1.554	**Vol_Jpy**	> -0.001***	-4.94	1.000 / 1.000	1.003				**Vol_USD (LAG)**	0.02	0.51	0.962 / 1.039	1.092
Vol_Gbp	10.30***	13.78	0.779 / 1.283	1.761	**Vol_Usd**	4e-3**	2.33	1.000 / 1.000	1.007				**Vol_GBP**	> 0.001***	5.74	0.999 / 1.000	1.217
Control_ GBPEUR	0.00***	3.87											**Control_ USDEUR**	42.39*	1.74		
NOBS	23,758				**NOBS**	53,792							**NOBS**	13390			
Adj. R^2	0.24				**Adj. R^2**	> 0.001							**Adj. R^2**	0.32			

Note: If we use a variable with a lag in our regression, the same variable without a lag is insignificant.
* Statistically significant at the 10% level.
** Statistically significant at the 5% level.
*** Statistically significant at the 1% level.

Table 5
Chow test of structural breaks in used time series. The results of the Chow test demonstrate if structural breaks in the time series at the beginning and the ending of the global financial crisis and the euro crisis exist.

Test statistics of equity markets			
Periods	**DJI**	**FTSE**	**N225**
NFC1-GFC	1141.36***	2682.11***	682.18***
GFC-NFC2	86.72***	389.38***	26.31***
NFC2-EURO	363.18***	99.41***	22.80***

Test statistics of exchange rates						
Periods	**USD/EUR**	**USD/GBP**	**USD/JPY**	**GBP/EUR**	**GBP/JPY**	**JPY/EUR**
NFC1-GFC	977.95***	1425.94***	298.18***	11.63***	20.27***	4731.05***
GFC-NFC2	243.67***	732.31***	79.99***	1838.78***	0.57	1906.71***
NFC2-EURO	208.72***	861.99***	101.46***	9459.30***	3031.69***	1706.47***

Note: GBP/USD, JPY/USD, JPY/GBP have the same test statistics as their opposing exchange rates.
* Statistically significant at the 10% level. ** Statistically significant at the 5% level.
*** Statistically significant at the 1% level.

Table 6
Volatility spillover between equity markets in financial crises. Table 6 presents the volatility spillover effects between equity markets for the global financial crisis and euro crisis periods. Alphas are the coefficients of the regression between the volatility of each equity market to other equity markets using the Newey-West method. The t-values under (*EURO-GFC)* demonstrate if the coefficients of both the GFC and the EURO are significantly different. $\sigma^2_{EQ,i}=\alpha_{i,0}+\sum_{k=0}^{n}\alpha_{i,k}\sigma^2_{EQ,k}+dummy_{fc}*\sigma^2_{EQ,k}+\varepsilon_{i,k}$ -
With $dummy\_fc=\begin{cases}0 & for\ GFC\\ 1 & for\ Euro\ Crisis\end{cases}$

Variable	Alpha	T-Value	Variable	Alpha	T-Value	*EURO-GFC*
GFC			***EURO***			
DJI						
Intercept	0.04	1.33	**Intercept**	0.17***	6.83	
Ftse(Overlap)	0.60***	3.16	**Ftse (Overlap)**	0.95***	11.69	3.34***
N225 (Close)	0.44***	4.89	**N225 (Close)**	0.03***	2.61	-3.75***
NOBS	407		**NOBS**	879		
Adj. R²	0.91		**Adj. R²**	0.71		
FTSE1						
Intercept	0.13***	3.74	**Intercept**	0.26***	7.66	
N225 (Close)	0.39***	7.16	**N225 (Close)**	0.13*	1.93	-2.25**
NOBS	416		**NOBS**	858		
Adj. R²	0.77		**Adj. R²**	0.06		
FTSE2						
Intercept	0.08***	4.05	**Intercept**	-0.02*	-1.84	
DJI (overlap)	0.56***	16.59	**DJI (overlap)**	0.03***	27.26	-1.90*
NOBS	1465		**NOBS**	5158		
Adj. R²	0.81		**Adj. R²**	0.59		
N225						
Intercept	-0.02	-0.38	**Intercept**	0.37***	9.08	
DJI (Close)	1.23***	5.36	**DJI (Close)**	0.33	1.04	-0.04
FTSE (Close)	0.02	0.06	**FTSE (Close)**	0.13	0.33	-0.44
NOBS	251		**NOBS**	310		
Adj. R²	0.86		**Adj. R²**	0.06		

Note: *NOBS* are calculated by time period in years multiplied by trading days per year multiplied by the number of opening hours. Variations in *NOBS* among the equity markets are mainly due to different opening hours (Tokyo Stock Exchange: 5 h, London Stock Exchange: 8.5 h and New York Stock Exchange 6.5 h) and the different lengths of sample time periods (GFC from 02/04/2007 to 06/01/2009 and euro crisis from 20/10/2010 to 26/04/2013).
* Statistically significant at the 10% level.
** Statistically significant at the 5% level.
*** Statistically significant at the 1% level.

Table 7
Volatility spillover between exchange rates and equity markets in financial crises. Table 7 shows the volatility spillover effects between exchange rates to equity markets for the two subsamples global financial crisis and euro crisis. Alphas are the coefficients of the regression between the volatility of each equity market to the volatilities of the exchange rates using the Newey-West method. The t-values in (EURO-GFC) demonstrate if the coefficients of the subsamples GFC and EURO are significantly different. $\sigma^2_{EQ,i}=\alpha_{i,0}+\sum_{k=0}^{n}\alpha_{i,k}\sigma^2_{EX,k}+dummy\_fc*\sigma^2_{EX,k}+\varepsilon_{i,k}$ -
With $dummy\_fc=\begin{cases}0 & for\ GFC\\ 1 & for\ Euro\ Crisis\end{cases}$

Variable	Alpha	T-Value	Variable	Alpha	T-Value	*EURO-GFC*
GFC			***EURO***			
DJI						
Intercept	-1.41***	-2.85	**Intercept**	0.46***	64.96	
Vol_EUR (LAG)	87.65**	1.98	**Vol_EUR**	15.71*	1.83	-1.98**
Vol_GBP	9.70***	6.25	**Vol_GBP**	1.34***	2.60	-5.45***
Vol_JPY	-1.71*	-1.70	**Vol_JPY**	-0.61***	-2.66	-1.86*
NOBS	3106		**NOBS**	6828		
Adj. R²	0.75		**Adj. R²**	0.01		
FTSE						
Intercept	0.10***	8.70	**Intercept**	0.21***	28.19	
Vol_USD	10.09***	15.10	**Vol_USD**	2.15***	9.67	-8.36***
Vol_EUR	0.10***	4.31	**Vol_EUR**	0.13***	10.37	2.81***
Vol_JPY	-0.00***	-5.70	**Vol_JPY (LAG)**	-0.00**	-1.34	-2.32**
NOBS	5142		**NOBS**	9750		
Adj. R²	0.38		**Adj. R²**	0.16		
N225						
Intercept	0.20***	5.55	**Intercept**	0.46***	15.77	
Vol_USD	-3.80***	-2.88	**Vol_USD (LAG)**	-1.24*	-1.65	2.66***
Vol_EUR	8.92***	14.13	**Vol_EUR (LAG)**	0.76	1.04	-6.72***
Vol_GBP (LAG)	0.00	0.95	**Vol_GBP**	0.04**	2.13	-0.71
NOBS	2154		**NOBS**	3815		
Adj. R²	0.65		**Adj. R²**	0.20		

Note: *NOBS* are calculated by time period in years multiplied by trading days per year multiplied by the number of opening hours. Variations in *NOBS* among the equity markets are mainly due to different opening hours (Tokyo Stock Exchange: 5 h, London Stock Exchange: 8.5 h and New York Stock Exchange 6.5 h) and the different lengths of sample time periods (GFC from 02/04/2007 to 06/01/2009 and euro crisis from 20/10/2010 to 26/04/2013). If we use a variable with a lag in our regression, the same variable without a lag is insignificant.
* Statistically significant at the 10% level.
** Statistically significant at the 5% level.
*** Statistically significant at the 1% level.

positive influence on the FTSE 100 except for the GBP/JPY. Of the three exchange rates, GBP/EUR is the only one which exhibits a higher volatility spillover in the euro crisis compared to the GFC.

For the N225, we find negative volatility spillover from the JPY/USD in both crises, consistent with the previous analysis of the volatility spillover between the USD/JPY to the DJI and the GBP/JPY to the FTSE 100. We also find positive volatility spillover for the JPY/EUR and the JPY/GBP in the euro crisis and the GFC respectively.

The results confirm our hypothesis that significant volatility spillover occurs between the exchange rate markets and the equity markets. The JPY based exchange rates reveal a negative volatility spillover against the equity markets which may be justified with an adaptation to the theory presented by Karoui (2006). A negative volatility spillover is possible when firms listed in the equity markets carry out high levels of trade with Japanese firms because the treasuries of such firms tend to carry out hedging in order to lower exchange rate risk.

Most of the exchange rates show a reduced volatility spillover during the euro crisis compared to the GFC, suggesting that firms may have increased their use of hedging instruments to reduce volatility risks between markets since the GFC. Furthermore, as suggested by Bekaert and Harvey (1997), the correlation often increases with market liberalizations. This suggests that governments may have introduced tighter regulatory procedures since the GFC in order to reduce volatilities in markets.

5.4. Determinants of Contagion

We control for periods of financial crises by implementing crisis indicators (Coudert et al. (2011)) instead of the subsampling approach. Additionally, we test the determinants of volatility spillover under the theoretical framework of “fundamental contagion” and “pure contagion” by controlling for macroeconomic factors (trade-balance, inflation and interest rate) and irrational investors’ behavior (trade volume, block volume and price error variance) respectively. The examination is concentrated on the DJI due to the significant volatility spillover effects in the GFC and the euro crisis previously found.

We test the crisis indicators for endogeneity in order to identify the appropriate indicators for the GFC and the euro crisis. Table 8 shows the results of a Durbin-Wu-Hausman test. In case of the GFC, the TED-Spread (TED) does not show endogeneity for both regressions and is used as an indicator. Additionally, the Durbin-Wu-Hausman Test shows that the abnormal euro yields (Euro_spread) are applicable for the analysis of volatility spillover between exchange rates and equity markets as an indicator for the euro crisis. However, the Euro_spread shows endogeneity for the analysis of volatility spillover between equity markets and therefore we use the instrument variable ZEW as an indicator for the euro crisis.

Table 9 shows the results of the regression of the volatility of the DJI against the volatilities of the FTSE 100 and the N225 for the GFC (Model 1) and the Euro Crisis (Model 2). The regression tests whether fundamental contagion (T-Notes, trade-balance and inflation) and pure contagion (log volume, PEV and ratio block volume to total trading volume) explain volatility spillover changes.

Table 9
Determinants of DJI volatility spillover changes between equity markets. Table 9 presents the estimates of the regression of the volatility of the DJI against the volatilities of other equity markets (Vol_FTSE and Vol_N225) including a crisis indicator for the GFC (Model 1) and the Euro Crisis (Model 2). The regression controls for fundamental contagion (T-Notes, trade-balance and inflation) and pure contagion (log volume, PEV and ratio block volume to total trading volume) described by regression coefficient $\gamma_j.\sigma^2_{DJI}=\alpha_{DJI,0}+\sum_{k=0}^{n}\alpha_{DJI,k}\sigma^2_{EQ,k}+\beta_i*TED/ZEW+\sum_{j=0}^{m}\gamma_j\sigma^2_{EQ,j}+\varepsilon_{DJI,TED/ZWE}$

Variable	Estimate	T-Value	Variable	Estimate	T-Value
Model 1 (GFC)			**Model 2 (EURO)**		
Intercept	-29.74	-1.34	**Intercept**	-46.44*	-1.84
Vol_FTSE	0.76***	6.30	**Vol_FTSE**	0.74***	6.33
Vol_N225	0.28***	3.74	**Vol_N225**	0.31***	4.29
TED	0.06**	2.13	**TED**	.	.
Euro_spread	.	.	**ZEW**	0.02***	2.88
T-Notes	-0.43	-1.38	**T-Notes**	-0.13	-0.47
Trade-Balance	< -0.001	-0.50	**Trade-Balance**	-0.001	-0.63
Inflation	-0.38**	-2.07	**Inflation**	-0.48**	-2.29
Volume	0.10	0.13	**Volume**	0.38	0.48
PEV	89,343	0.70	**PEV**	103,964	0.81
B/V	43.26**	2.13	**B/V**	54.25***	2.85
NOBS	135		**NOBS**	102	
Adj. R^2	0.95		**Adj. R^2**	0.96	

* Statistically significant at the 10% level.
** Statistically significant at the 5% level.
*** Statistically significant at the 1% level.

We find significant positive volatility spillover increases from the FTSE 100 and the N225 to the DJI in the GFC and the euro crisis. This increase in volatility spillover is explained by inflation and information asymmetry (B/V).

These findings confirm our hypothesis that volatility spillover increases between equity markets are explained in part by fundamental and pure contagion in financial crises. The significant ratio between the block volume and the total volume (B/V) demonstrates that information asymmetries between institutional and private investors occur and lead to an increase in volatility spillover. We provide empirical evidence to confirm the theory suggested by Calvo and Mendoza (2000) and Lin et al. (1994) that price movements are driven by fads and herd instincts may transmit across borders.

Table 10 shows the results of the regression of the volatility of the DJI against the volatilities of the USD/EUR (Vol_EUR), USD/GBP (Vol_GBP) and USD/JPY (Vol_JPY) for the GFC (Model 1) and the Euro Crisis (Model 2). The regression tests whether fundamental contagion (T-Notes, trade-balance and inflation) and pure contagion (log volume, PEV and ratio block volume to total trading volume) explain the volatility spillover changes.

During the euro crisis, the volatility spillover increased from the USD/GBP to the DJI and decreased from the USD/EUR to the DJI. The additional controls for fundamental contagion and pure contagion show that all factors except liquidity (trading volume) influence the

Table 8
Durbin-Wu-Hausman test for endogeneity. The two-stage Durbin-Wu-Hausman Test tests our indicator variables for endogeneity by comparing the instrument variable estimates to OLS estimates. **EQ** refers to the equity markets volatility spillover contagion analysis and **EXR & EQ** refers to the volatility spillover contagion analysis between the exchange rate markets and the equity markets. The Case-Shiller Home Price Index is used as an instrumental variable for the TED-Spread variable for the GFC. The ZEW is used as an instrumental variable for the abnormal euro spread (Euro_spread) for the EURO crisis. The significance of the Hausman *t*-test results determines the cursive variables that we apply in the ensuing analyses.

	Variable	Instrument	Hausman *t*-test	Variable	Instrument	Hausman *t*-test
	GFC			**EURO**		
EQ	*TED*	Case-Shiller Home Price Index	0.64	Euro_spread	*ZEW*	-2.67***
EXR & EQ	*TED*	Case-Shiller Home Price Index	0.44	*Euro_spread*	ZEW	0.61

Note: *Statistically significant at the 10% level. ** Statistically significant at the 5% level.
*** Statistically significant at the 1% level.

Table 10
Determinants of DJI volatility spillover from EXR to EQ. Table 10 presents the estimates of the regression of the volatility of the DJI against the volatilities of the exchange rate markets (Vol_EUR, Vol_GBP and Vol_JPY) including a crisis indicator for the GFC (Model 1) and the Euro Crisis (Model 2). The regression controls for fundamental contagion (T-Notes, trade-balance and inflation) and pure contagion (log volume, PEV and ratio block volume to total trading volume) described by the regression's coefficient $\gamma_j.\sigma^2_{DJI}=\alpha_{k,0}+\sum_{k=0}^{n}\alpha_k\sigma^2_{EXR,k}+\beta_i*TED/ZEW+\sum_{j=0}^{m}\gamma_j\sigma^2_{EQ,j}+\varepsilon$

Variable	Estimate	T-Value	Variable	Estimate	T-Value
Model 1 (GFC)			**Model 2 (EURO)**		
Intercept	-57.56	-0.65	**Intercept**	-80.14	-0.69
Vol_EUR	0.00	0.23	**Vol_EUR**	-59.21***	-3.26
Vol_GBP	-0.06	-0.15	**Vol_GBP**	2.35***	2.65
Vol_JPY	-1.35	-1.32	**Vol_JPY**	-0.20	-0.24
TED	0.45**	2.23	**TED**	.	.
Euro_spread	.	.	**Euro_spread**	0.25***	3.44
T-Notes	-3.41***	-3.97	**T-Notes**	-8.67***	-6.06
Trade-Balance	-0.002	-1.59	**Trade-Balance**	-0.008***	-2.93
Inflation	-2.76***	-2.77	**Inflation**	-3.87***	-2.85
Volume	-2.21	-0.83	**Volume**	-2.54	-0.69
PEV	> 1 m***	33.30	**PEV**	> 1 m***	20.05
B/V	273.84**	2.61	**B/V**	276.92***	3.99
NOBS	136		**NOBS**	103	
Adj. R^2	0.96		**Adj. R^2**	0.97	

Note: *Statistically significant at the 10% level,
** Statistically significant at the 5% level.
*** Statistically significant at the 1% level.

volatility spillover changes between the USD/EUR and the USD/GBP to the DJI. These results are consistent with the explanations in Karoui (2006), who suggests that a depreciation of a local currency increases (decreases) the income of an exporting (importing) firm. As a result, the sign of the correlation between exchange rates and stock prices depends on the net position of local currency of a firm. Further, investors who have already invested in local stocks will seek other financial markets which may be more profitable. In contrast, those investors who have not invested will find these stocks cheap and buy. Therefore, during the euro crisis, when the GBP and EUR were most susceptible to macroeconomic shocks, firms and investors' behavior are expected to play a role in determining the sign of the correlation between the volatilities of exchange rates and stock prices. Liquidity problems of investors as suggested by Hernández and Valdés (2001) do not seem to affect volatility spillover in the case of the DJI.

In the case of the global financial crisis, the exchange rate markets reveal no significant volatility spillover to the DJI. This suggests that the volatility of the DJI may be driven by localized macroeconomic and pure contagions.

6. Conclusion

We analyze the volatility spillover effect between the DJI, FTSE 100 and N225 equity markets as well as their underlying exchange rates over the period 2001 through 2013 on an hourly basis. We use the Chow-Test to delineate the structural break between the times series of the global financial crisis and the euro debt crisis. The innovation of this paper involves investigating the determinants which explains contagion of volatility spillover between equity and exchange markets during the two crises. We examine whether investors' behavior leads to irrational phenomena like financial panics (pure contagion) in excess of that implied by macroeconomic fundamentals (fundamental contagion).

Our results show that equity markets exhibit significant positive volatility spillover (except between FTSE to N225) showing that the risk of equity markets from one market's closing period is transmitted to the next equity market's opening period. These results are in line with prior studies such as Lin et al. (1994) and confirm the meteor shower effect of Engle et al. (1990).

In addition, we show that significant positive volatility spillover from exchange rates to equity markets exists (except JPY/USD to N225). The volatility of exchange rates is transmitted to the equity markets within one hour (except USD/EUR to DJI where it is transmitted within two hours). The findings indicate that the risk of exchange rates increases the risk in equity markets for our whole data sample, which is contrary to the results of Kansas (2000).

We find that contagion between equity markets is explained by inflation and information asymmetry between investors in the global financial crisis and the euro crisis. It shows that irrational investors' behavior could lead to financial panics in crises and the volatility spillover increases in excess of macroeconomic fundamentals. These results are consistent with Kodres and Pritsker (2002) and confirm the "pure contagion" theory.

We provide evidence that contagion from exchange rates to the DJI in the euro debt crisis is influenced by macroeconomic fundamentals and proxies of investors' behavior except liquidity. It indicates that investors' behavior also influences the volatility spillover from exchange rates to equity markets in the euro crisis in excess of that implied by macroeconomic fundamentals. Again, this confirms the theory of "pure contagion" by Kodres and Pritsker (2002) and shows that imperfect information (Fleming et al. (1998)) and information asymmetry (Calvo and Mendoza (2000)) leads to irrational behavior in the euro crisis.

Future work could examine whether different market microstructure measures of market efficiency or market quality may impact volatility spillover. We already broached this issue by using the price error variance as a proxy for market efficiency, but a more detailed analysis using other measures is warranted.

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