Interdependence and volatility spillover among the euro, pound sterling and Swiss franc

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Working Paper No.226

October, 2007

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Abstract

To examine interdependence and volatility spillover among the euro, pound sterling and Swiss franc, we employ the dynamic conditional correlation model of multivariate generalized autoregressive conditional heteroskedasticity. Our main findings are: 1) a shock in the return volatility of the euro spills over into pound sterling and the Swiss franc; and 2) these markets are highly integrated with the euro, the degree of interdependence being state dependent. Euro news has a simultaneous impact on pound sterling and the Swiss franc, co-movements of these currencies and the euro becoming much higher in proportion to news arrival of the euro.

JEL classification: F31; F33; G15

Keywords: DCC MV-GARCH; High frequency data; Information; Interdependence; Volatility spillover

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1. Introduction

This study examines the causality in return variances and the interdependence of the euro, pound sterling and Swiss franc foreign exchange spot (FX) markets. The term *interdependence* corresponds to any continued market correlation at high levels (see, for example, Chiang et al., 2007).

While the dynamics of these three currencies, such as the interdependence and the causality among them, is well observed and known by not only traders but also academic researchers, there is still room for research questions on their intraday dynamics: Is the degree of interdependence among them state dependent or not? What intraday reaction do pound sterling and Swiss franc volatilities show after a shock in the return volatility of the euro? Of course, there are a number of studies which focus on hourly and daily dynamics of these currencies (e.g., Malik, 2005; Nikkinen et al., 2005; Inagaki, 2007). The aim of this study is to reinforce the extant literature to examine those dynamics in more detail using a 10-minute high frequency data set. To understand the details of the dynamics of the euro, pound sterling and Swiss franc is crucial for implementing hedging strategies and allocation decisions among assets evaluated by those currencies.

This study employs the dynamic conditional correlation (DCC) model of multivariate generalized autoregressive conditional heteroskedasticity (MV-GARCH) developed by Engle (2002), and Tse and Tsui (2002) to capture the intraday dynamics of the euro, pound sterling and the Swiss franc. The virtues of this model are: 1) to estimate fewer parameters than the other models (e.g., BEKK, introduced by Engle and Kroner, 1995); and 2) to overcome the issue of positive definition of the variance-covariance matrix, which frequently causes problems in the extant models in executing their estimation.

Moreover, the DCC MV-GARCH model poses a general assumption on the correlation coefficient that is time variant. This enables us to examine what is the underlying driving factor of movement of a correlation coefficient: if a correlation coefficient is time variant, at which timing does it reach its peak and which factors explain such high level correlations between currency returns?

The rest of this paper is organized as follows. The next section provides information on our data set. Section 3 introduces the DCC MV-GARCH model that considers the causality in returns and variances of the euro/pound sterling and euro/Swiss franc currency pairs, respectively. Section 4 shows the estimation results of the DCC MV-GARCH model and examines the details of the dynamics of those pairs. The last section concludes our research.

2. The data

The data set was purchased from electronic broking system (EBS) corporation. The sample period runs from April 2 to August 31, 2006. Throughout this period, America and Europe adopted daylight saving time (DST). Therefore, we need not consider a change of intraday seasonality in the FX market, caused by the timing of the adoption of DST by each country (Ito and Hashimoto, 2006). We exclude all data collected from Friday 23:30 Greenwich Mean Time (GMT) to Sunday 23:30 GMT from our sample since trading activity during these hours is minimal.

The data set is created in periods of one-second time slices comprising a Price Record and a Deal Record. The Price Record lists the EBS best bid/ask prices at the end of a time slice. The Deal Record lists the highest paid and lowest given deal prices during the period of the time slice. No information about trading volume or order type (market or limit order) is available. With a Deal Record, we construct a trade indicator that takes 1 (-1) when a paid (given) rate shows up in the Deal Record. If there is no deal in the EBS system, that indicator takes zero. In our sample, neither the paid nor given rates are recorded at the same second for any of the currencies.

We convert the original data set into 10-minute intervals. We employ as a price S_t, the midpoint quote of the best bid and ask rates observed lastly in each interval. A return of each currency is defined as $R_t = 100 \times \ln(S_t/S_{t-1})$.

By summing up trade indicators in each interval, we calculate order flow (buyer initiated trades minus seller initiated trades). Recent studies (e.g., Evans and Lyons, 2002) stress the role of order flow which conveys a signal of private information and fundamentals. We calculate the order flow of each currency in each 10-minute interval for the empirical approach in the next section.

Table 1.

Table 1 reports the summary statistics of the first and the second moments of returns and order flows of the three currencies. For the second moment of the returns, the Ljung-Box test statistics shows strong evidence of non-linear dependency for all the currencies, leading us to select the GARCH framework to capture the dynamics of return volatility.[1]

It is well documented that a volatility of an FX rate return shows intraday seasonality (e.g., Ballie and Bollerslev, 1990; Ito and Hashimoto, 2006). This might induce us to select a longer GARCH lag term because longer lags capture the spikes due to seasonality. However, to save the number of estimated parameters, we remove the seasonality of volatility.

Figure 1.

Figure 1 shows averaged squared returns of each currency in each interval. We observe the intraday U-shape pattern of averaged squared returns, the peaks corresponding to the timing of the opening and closing of the major markets, namely, the London and New York markets.[2] To remove such seasonality, we divide the sample returns by the root of five interval moving average of averaged squared returns. The bold line in Figure 1 is the moving average and plotted circles are averaged squared returns in each interval. Since we also observe seasonality in the squared order flows, which is quite similar to that of the squared returns, we remove the seasonality of the order flows using the same method adopted for squared returns.

3. The model

This section utilizes the DCC MV-GARCH model to examine details of the intraday dynamics in the euro, pound sterling and Swiss franc. In the DCC MV-GARCH model, we consider the causality in the first and second moments of the

[1] The Ljung-Box test statistics for variable y is $T(T+2)\sum_{k=1}^{6} r_k^2 /(T-K)$, where T is a sample size and $r_k = \sum_{t=k+1}^{T}(y_t - \bar{y})(y_{t-k} - \bar{y}) / \sum_{t=1}^{T}(y_t - \bar{y})^2$.

[2] When both Europe and America adopt DST, Melvin and Melvin (2003) identify 5:30-15:30 and 11:30-20:00 GMT as the business hours of Europe and America, respectively.

returns of the three currencies. For this, we adopt the Granger causality test for the first and the second moments of the returns of the euro and currency i ($i=$ *gbp* [pound sterling] and *chf* [the Swiss franc]) prior to estimation of the DCC MV-GARCH model.

Table 2.

The Granger χ^2 test statistics is calculated with the Newey and West variance-covariance matrix.[3] The lag selection rule of the Granger test is based on the Akaike (AIC), Schwarz (SC) and Hannan-Quinn (HQ) criteria. Table 2 shows the Granger causality from the euro to both pound sterling and the Swiss franc in the first and the second moments, respectively. Moreover, we also observe the causality from pound sterling to the euro in the second moment even though the value of the summed coefficients of pound sterling is relatively small.

First, the results from Table 2 lead us to set the following return equations:

$$\begin{pmatrix} R_{euro,t} \\ R_{i,t} \end{pmatrix} = \begin{pmatrix} a_{euro} \\ a_i \end{pmatrix} + \begin{pmatrix} b_{euro,1} & 0 \\ b_{euro,2} & b_{i,2} \end{pmatrix} \begin{pmatrix} R_{euro,t-1} \\ R_{i,t-1} \end{pmatrix} + \begin{pmatrix} d_{euro} X_{euro,t} \\ d_i X_{i,t} \end{pmatrix} + \begin{pmatrix} e_{euro,t} \\ e_{i,t} \end{pmatrix} \tag{1}$$

$$e_t \mid \Phi_{t-1} = \begin{pmatrix} e_{euro,t} \\ e_{i,t} \end{pmatrix} \sim N(0, \Omega_t), \tag{2}$$

where Φ_{t-1} is an available information set at past time $t-1$, and $i=$ *gbp* (pound sterling), *chf* (Swiss franc). $R_{i,t}$ is currency i's return ($100 \times \ln(S_t/S_{t-1})$, where S_t is the United States dollar spot rate quoted against each currency). $X_{i,t}$ is the order flow of currency i. As explained in the previous section, R and X are seasonally adjusted. In the above return equations we consider the one-way causality from the euro to currency i, which is consistent with the result in Table 2.

Next, we model the conditional volatilities depicted as follows:

$$\begin{pmatrix} h_{euro,t} \\ h_{i,t} \end{pmatrix} = \begin{pmatrix} \omega_{euro} \\ \omega_i \end{pmatrix} + \begin{pmatrix} \alpha_{euro} e^2_{euro,t-1} \\ \alpha_i e^2_{i,t} \end{pmatrix} + \begin{pmatrix} \beta_{euro,1} & \beta_{i,1} \\ \beta_{euro,2} & \beta_{i,2} \end{pmatrix} \begin{pmatrix} h_{euro,t-1} \\ h_{i,t-1} \end{pmatrix}, \tag{3}$$

where $h_{i,t}$ is a conditional variance of currency i in period t. Table 2 indicates that the past volatility of the euro has an impact on those of pound sterling and the Swiss franc. Moreover, even if its effect might be small, there could also be causality from

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[3]The lag of the Newey and West variance-covariance matrix is $T^{1/4}$, where T is the sample size.

pound sterling to the euro in the second moments. Therefore, we restrict $\beta_{i,1} = 0$ when $i = chf$ in Eq. (3).

Engle (2002), and Tse and Tsui (2002) model the variance-covariance matrix Ω_t as follows:

$$\Omega_t = D_t \Gamma_t D_t = \begin{pmatrix} h_{euro,t}^{1/2} & 0 \\ 0 & h_{i,t}^{1/2} \end{pmatrix} \begin{pmatrix} 1 & \rho_{i,t} \\ \rho_{i,t} & 1 \end{pmatrix} \begin{pmatrix} h_{euro,t}^{1/2} & 0 \\ 0 & h_{i,t}^{1/2} \end{pmatrix}, \tag{4}$$

where $\rho_{i,t}$ is the correlation coefficient between $e_{euro,t}$ and $e_{i,t}$. Since $|\rho_{i,t}| < 1$ and $h_{euro,t}, h_{i,t} > 0$ hold generally, all the principal minors of matrix Ω_t are above zero. This is a necessary and sufficient condition for a positive definite matrix of Ω_t (*see* Theorem 1.E.11 in Takayama [1985]).

Following Tse and Tsui (2002), time variant $\rho_{i,t}$ in Eq. (4) is specified as follows:

$$\rho_{i,t} = (1 - \theta_1 - \theta_2)\rho + \theta_1 \rho_{i,t-1} + \theta_2 \psi_{t-1}, \tag{5}$$

$$\text{where } \psi_{t-1} = \frac{\sum_{k=1}^{2} \varepsilon_{euro,t-k} \varepsilon_{i,t-k}}{\sqrt{(\sum_{k=1}^{2} \varepsilon_{euro,t-k}^2)(\sum_{k=1}^{2} \varepsilon_{i,t-k}^2)}} \quad \text{with } \varepsilon_{i,t} = e_{i,t}/h_{i,t}.$$

With an assumption of normality in Eq. (2) and from Eq. (4), we specify the log likelihood function $\ln L$ and obtain the set of parameters $\hat{\Theta}$ that maximizes $\ln L(\Theta)$ as follows:

$$\ln L(\Theta) = -\frac{T}{2}\ln 2\pi - \frac{1}{2}\sum_{t=1}^{T} \ln|\Omega_t(\Theta)| - \frac{1}{2}\sum_{t=1}^{T} e_t(\Theta)' \Omega_t(\Theta)^{-1} e_t(\Theta). \tag{6}$$

The adopted routine to maximize Eq. (6) is the Berndt, Hall, Hall and Hausman (BHHH) algorithm. A variance-covariance matrix of estimated parameter $\hat{\Theta}$ is evaluated with the *sandwich estimator* (White, 1982), which is valid even if the probability density in Eq. (2) is misspecified. Therefore, obtained estimators are quasi-maximum likelihood ones which are valid even if the residuals from the model in Eq. (2) are not normally distributed. This enables us to draw the usual statistical inferences from the estimated parameters.

4. The results

Table 3.

Table 3 reports the estimation results of the DCC MV-GARCH model obtained from the maximization of Eq. (6) for each pair of currencies (euro/pound sterling and euro/Swiss franc).

First, Table 3 shows a strong GARCH effect in the conditional volatilities of all the currencies. This finding is consistent with the extant empirical literature and also with the mixture distribution hypothesis, which suggests that when we approximate the stochastic process of arrival information with autoregressive process, the return volatility shows a GARCH process (Anderson, 1996). Since the Ljung-Box test statistics indicates a serial correlation of the squared standardized residual, we also estimate a model that includes first- and second-order ARCH terms in each case and confirm that it does not substantially change our findings below (the results are available upon request). Therefore, we develop the following discussion based on the models in Eqs. (1)-(5).

Secondly, we observe the spillover effect from the euro to both pound sterling and the Swiss franc in the first and second moments.

In the return equation of both pound sterling and the Swiss franc, the parameter $b_{euro,2}$, the spillover effect in mean equation, shows a positive value and is statistically significant. This indicates that there is a no substitution effect from the euro to either of these two currencies.

We also observe the spillover effect in the conditional volatilities from the euro to both pound sterling and the Swiss franc. The effects are calculated with a value of $\beta_{euro,2}$ in Eq. (3). The estimated $\beta_{euro,2}$ shows a positive value and is statistically significant in both the pound sterling and Swiss franc volatility equations. To show that effect visually, we calculate an impulse response function from Eq. (3). Let $h_t = (h_{euro,t}, h_{i,t})'$ represent the 2 × 1 vector of conditional volatilities in period t, and let $e_t^2 = (e_{euro,t}^2, e_{i,t}^2)'$ be the 2 × 1 vector of squared innovations of Eq. (1) in period t. Note $E_{t-1}[e_t^2 \mid \Phi_{t-1}] = E_{t-1}[h_t]$. We can obtain the following s step ahead of predictions:

$$h_{t+s}^* = \omega + (A+B)^s h_t^*, \tag{7}$$

$$\frac{\partial h_{t+s}^{*}}{\partial h_{t}^{*'}} = (A+B)^{s} \tag{8}$$

$$\omega = \begin{pmatrix} \omega_{euro} \\ \omega_{i} \end{pmatrix} \quad A = \begin{pmatrix} \alpha_{euro} & 0 \\ 0 & \alpha_{i} \end{pmatrix} \quad B = \begin{pmatrix} \beta_{euro,1} & \beta_{i,1} \\ \beta_{euro,2} & \beta_{i,2} \end{pmatrix}.$$

The superscript * means an expected value in period $t-1$. Prime ("$'$") indicates a transportation matrix. Using Eq. (8) and estimated parameters in Table 3, we obtain impulse responses of pound sterling and the Swiss franc volatilities to a volatility shock in the euro in period t.

Figure 2.

The dotted line in Figure 2 is the estimated two-standard error boundary. We obtain the standard errors by linear approximation (*see* Appendix).

Figure 2 shows that the impact of shock in the return volatility of the euro on each currency reaches its peak after 11 (pound sterling, about 2 hours) and 6 (Swiss franc, 1 hour) periods, respectively. This implies that since a volatility shock in the euro brings an uncertainty to the pound sterling and Swiss franc markets, these markets become volatile for the first several periods after that shock. We also confirm that the impact of the euro volatility on each currency is not short-lived. Therefore, we conclude that the volatility spillover effect from the euro to both pound sterling and the Swiss franc is substantial and its impact long-lived.

Finally, we examine the dynamics of the conditional correlation between the euro and each currency. The conditional correlation parameters appearing in Table 3 are statistically significant for each pair of currencies (euro/pound sterling and euro/Swiss franc), consistent with the hypothesis that the conditional correlation of each pair is time variant.

Figure 3.

Figure 3 shows the averaged conditional correlation of each currency pair for each 10-minute interval. We confirm high level correlation in all intervals, providing empirical evidence for the interdependence between the euro and each currency. This implies that these three FX markets are highly integrated, leading us to suppose that such high level integration means that the markets share the same information that affects the FX rates. Moreover, from the results of the Granger causality test (Table 2) and the DCC MV-GARCH estimation (Table 3), it is natural to infer that information relevant to the euro also has an impact on pound sterling and the Swiss franc. To examine the validity of this inference, we model the dynamics of the cross correlation as follows:

$$\hat{\rho}_{i,t} = \tau + \sum_{p=1}^{q} \gamma_p \hat{\rho}_{i,t-p} + \sum_{n=1}^{23} \lambda_n hourD_n + \delta news\mathrm{EUR}, \tag{9}$$

where $\hat{\rho}_{i,t}$ is a cross correlation between the euro and currency i obtained by the estimation in Table 3. Since we model an autoregressive process of a cross correlation in Eq. (5), lagged terms are included in Eq. (9). Lag length q is selected by the AIC criterion.

Evans and Lyons (2002) assert that order flows, which are defined as the net of buyer-initiated trades, convey information on aggregate portfolio shifts and, therefore, have a substantial explanatory power to the dynamics of FX rates. Here, we define as news an unexpected component of the order flow of the euro as $news\mathrm{EUR}$. $news\mathrm{EUR}$ in Eq. (9) is calculated from the squared residuals of the ARMA(1,1) model of the euro order flow (*see* Table 4A).

$hourD_n$ is a dummy variable which takes unity at the nth GMT hour and otherwise zero. Figure 3 shows a seasonality of the cross correlations, which corresponds to the opening timings of the regions of three major markets, namely, the Tokyo, London and New York markets. To measure the pure effect of euro news on the interdependence, we remove the seasonality by introducing the GMT hour dummy variable $hourD_n$.

Table 4.

Table 4B reports the estimation result of Eq. (9). The number in parentheses is the standard error obtained from the Newey and West variance-covariance matrix. In both cases, the estimated δ is positive and statistically significant. This result is consistent with our inference that there is information spillover from the euro to pound sterling and the Swiss franc. It is reasonable to assume that unexpected selling of the euro enables market participants to infer aggregate portfolio shifts from the euro countries and also from the United Kingdom (UK) and Switzerland: Since a negative economic shock to the euro area also has a negative impact on the UK and Switzerland, traders shift their assets from these areas. Consequently, unexpected selling of the euro induces market participants to sell these currencies accompanied by portfolio reshuffling. Therefore, unexpected selling of the euro can also have a negative impact on pound sterling and the Swiss franc. This inference is consistent with the sign of δ in Table 4B.

The above confirmation is not very surprising. The euro countries, the UK and Switzerland share common economic and political backgrounds due to their geographic proximity. Moreover, smaller Switzerland heavily relies on its neighboring euro countries and is affected by the economic situation of those countries. The UK, which is bigger than Switzerland, is also affected by the euro area. The results of Figures 2 and 3 indicate that the euro and the pound sterling markets are relatively less integrated than the euro and Swiss franc markets.

5. Conclusion

The findings of this paper provide two major contributions: First, the euro, pound sterling and Swiss franc markets are highly integrated, the latter two currencies being substantially affected by the euro. A volatility shock in the euro brings about uncertainty to the pound sterling and Swiss franc markets for several intervals. The result of the empirical approach implies that news of the euro spills over into the pound sterling and the Swiss franc markets and, consequently, the euro and the two currencies (pound sterling and Swiss franc) show highly positive co-movement. This is explained by the common economic and political backgrounds which the euro countries, the UK and Switzerland share due to their geographic proximity.

Secondly, although the level of integration between the euro and pound sterling markets is high, they are less integrated than the euro and Swiss franc markets.

If such high integration in the euro, pound sterling and Swiss franc is universal, the UK and Switzerland would have little incentive to join the European Monetary Union because they can enjoy the degree of freedom in executing their monetary policy that would be lost by giving up their own currencies.

Appendix

Denoting that $D(\Xi)^s = (A+B)^s$, $\Xi = [\alpha_{euro}, \beta_{euro,1}, \beta_{i,1}, \alpha_i, \beta_{euro,2}, \beta_{i,2}]'$ and $\hat{\Xi}$ is a set of estimated parameters, we obtain the first order linear approximation of $D(\Xi)^s$ around $\hat{\Xi}$ as follows:

$$
\begin{aligned}
D(\Xi)^s &\simeq D(\hat{\Xi})^s + \frac{\partial D(\hat{\Xi})^s}{\partial \Xi'}(\Xi - \hat{\Xi}) \\
\mathrm{vec}[D(\Xi)^s] &= \mathrm{vec}[D(\hat{\Xi})^s] + \left[\sum_{i=0}^{s-1} [D(\hat{\Xi})']^{s-1-i} \otimes D(\hat{\Xi})^i\right] \frac{\partial \mathrm{vec}[D(\hat{\Xi})]}{\partial \Xi'}(\Xi - \hat{\Xi}),
\end{aligned}
\tag{A1}
$$

where "vec" creates a column vector by appending the columns of a matrix to each other. $\otimes$ is the Kronecker product. $y \otimes z$ results in a matrix in which every element in y has been multiplied by matrix z. The second line in Eq. (A1) is derived from the result of Lütkepohl (1993, p.471)

With Eq. (A1), we obtain the following variance-covariance matrix of $\mathrm{vec}[D(\Xi)^s]$:

$$
\mathrm{Var}(\mathrm{vec}[D(\hat{\Xi})^s]) = \left(\frac{\partial \mathrm{vec}[D(\hat{\Xi})^s]}{\partial \Xi'}\right) \mathrm{Var}(\hat{\Xi}) \left(\frac{\partial \mathrm{vec}[D(\hat{\Xi})^s]}{\partial \Xi'}\right)' \tag{A2}
$$

where

$$
\frac{\partial \mathrm{vec}[D(\hat{\Xi})^s]}{\partial \Xi'} = \left[\sum_{i=0}^{s-1} [D(\hat{\Xi})']^{s-1-i} \otimes D(\hat{\Xi})^i\right] \frac{\partial \mathrm{vec}[D(\hat{\Xi})]}{\partial \Xi'},
$$

where $\hat{\Xi}$ and $\mathrm{Var}(\hat{\Xi})$ are obtained from the maximization of Eq. (6).

References

Anderson, T.G., 1996. Return volatility and trading volume: an information flow interpretation of stochastic volatility. Journal of Finance 51(1), 169-204.

Baillie, R., Bollerslev, T., 1990. Intra-day and inter-market volatility in foreign exchange rates. Review of Economic Studies 58, 565-585.

Chiang, T.C., Jeon, B.N., Li, H., 2007. Dynamic correlation analysis of financial contagion: Evidence from Asian markets. Journal of International Money and Finance 26, 1206-1228.

Engle, R., 2002. Dynamics conditional correlation: A simple class of Multivariate generalized autoregressive conditional heteroskedasticity models. Journal of Business and Economic Statistics 20(3), 339-350.

Engle, R., Kroner, K., 1995. Multivariate simultaneous GARCH. Econometric Theory 11, 122-150.

Evans, M.D.D., Lyons, R.K., 2002. Order flow and exchange rate dynamics. Journal of Political Economy 110(1), 170-180.

Lütkepohl, H., 1993. Introduction to multiple time series analysis. 2nd ed. Springer-Verlag, Berlin, Germany

Inagaki, K., 2007. Testing for volatility spillover between the British pound and the euro. Research in International Business and Finance 21(2), 161-174.

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

Malik, A.K., 2005. European exchange rate volatility dynamics: an empirical investigation. Journal of Empirical Finance 12(1), 187-215.

Melvin, M., Melvin, B.P., 2003. The global transmission of volatility in the foreign exchange market. Review of Economics and Statistics. 85(3), 670-679.

Nikkinen, J., Sahlström, P., Vähämaa, S., 2005. Implied volatility linkages among major European currencies. Journal of International Financial Market, Institutions & Money. 16, 87-103.

Takayama, A., 1985. Mathematical economics. 2nd ed. Cambridge University Press, Cambridge, UK.

Tse, Y.K., Tsui, A.K., 2002. A multivariate generalized autoregressive conditional heteroskedasticity model with time-varying correlations. Journal of Business and Economic Statistics 20(3), 351-362.

White, H., 1982. Maximum likelihood estimation of misspecified models, Econometrica 50(1) 1-25.

Table 1

Summary of statistics

Variable	Mean	S.D.	First order serial correlation	LB(6)
R_{euro}	.00036	.045	-.02	26.2 ***
R_{gbp}	.00060	.046	-.04	27.2 ***
R_{chf}	.00037	.051	-.03	39.1 ***
R^2_{euro}	.00205	.009	.15	699.0 ***
R^2_{gbp}	.00210	.010	.15	567.8 ***
R^2_{chf}	.00263	.010	.18	915.0 ***
X_{euro}	.20789	12.623	.07	127.2 ***
X_{gbp}	.07170	3.720	.13	606.1 ***
X_{chf}	-.01743	7.332	.05	77.2 ***

Note: LB(6) is the Ljung-Box statistics with six lags. R, R^2 and X are the first and second moments of returns, and order flow of each currency (euro, pound sterling [*gbp*] and Swiss franc [*chf*]). *** indicates 1 percent level of significance. S.D.: standard deviation

Table 2

Granger χ^2 causality test

2A. Granger χ^2 causality test of *first* moment of returns

Direction of causality		Euro→Pound sterling			Pound sterling →Euro			Direction of causality		Euro→Swiss franc			Swiss franc→Euro		
Criterion	Lag	Sum of ζ_2	χ^2 stat	p-value	Sum of η_1	χ^2 stat	p-value	Criterion	Lag	Sum of ζ_2	χ^2 stat	p-value	Sum of η_1	χ^2 stat	p-value
AIC	7	0.215	46.855	(.000)	0.053	5.403	(.611)	AIC	6	0.264	73.505	(.000)	0.096	3.003	(.808)
SIC	2	0.160	41.179	(.000)	0.032	2.613	(.271)	SIC	2	0.238	69.054	(.000)	0.024	0.818	(.664)
HQ	3	0.204	46.246	(.000)	0.031	2.688	(.442)	HQ	3	0.260	68.607	(.000)	0.048	1.646	(.649)

2B. Granger χ^2 causality test of *second* moment of returns

Direction of causality		Euro→Pound sterling			Pound sterling→Euro			Direction of causality		Euro→Swiss franc			Swiss franc→Euro		
Criterion	Lag	Sum of κ_2	χ^2 stat	p-value	Sum of ν_1	χ^2 stat	p-value	Criterion	Lag	Sum of κ_2	χ^2 stat	p-value	Sum of ν_1	χ^2 stat	p-value
AIC	10	0.261	19.954	(.030)	0.051	23.926	(.008)	AIC	10	0.230	30.348	(.001)	0.036	7.876	(.641)
SIC	6	0.242	15.597	(.016)	0.056	16.570	(.011)	SIC	6	0.154	26.993	(.000)	0.056	3.164	(.788)
HQ	6	0.242	15.597	(.016)	0.056	16.570	(.011)	HQ	6	0.154	26.993	(.000)	0.056	3.164	(.788)

Note: The regression forms for the causality test of the first and the second moments of the returns are as follows:

$$R_{euro,t} = \text{cons} + \sum_{p=1}^{q} \zeta_{1,p} R_{euro,t-p} + \sum_{p=1}^{q} \eta_{1,p} R_{i,t-p} \qquad R^2_{euro,t} = \text{cons} + \sum_{p=1}^{q} \kappa_{1,p} R^2_{euro,t-p} + \sum_{p=1}^{q} \nu_{1,p} R^2_{i,t-p}$$

$$R_{i,t} = \text{cons} + \sum_{p=1}^{q} \zeta_{2,p} R_{euro,t-p} + \sum_{p=1}^{q} \eta_{2,p} R_{i,t-p}. \qquad R^2_{i,t} = \text{cons} + \sum_{p=1}^{q} \kappa_{2,p} R^2_{euro,t-p} + \sum_{p=1}^{q} \nu_{2,p} R^2_{i,t-p},$$

where *i*=*gbp* (pound sterling), *chf* (Swiss franc). Lag length q is selected by each criterion. The Granger χ^2 test statistics (χ^2 stat) is calculated with the Newey and West variance-covariance matrix. The lag of the Newey and West variance-covariance matrix is $T^{1/4}$, where T is the sample size.

Table 3

Estimation results of DCC MV-GARCH model

Pair of returns: $R_{euro,t}$ and $R_{gbp,t}$

	Euro Estimates			Pound sterling (gbp) Estimates	
a_{euro}	.000	(.002)	a_{gbp}	.012 ***	(.004)
$b_{euro,1}$	-.021 **	(.010)	$b_{euro,2}$	-.135 ***	(.012)
			$b_{gbp,2}$	.125 ***	(.013)
d_{euro}	.163 ***	(.006)	d_{gbp}	.089 ***	(.007)
ω_{euro}	.029 ***	(.010)	ω_{gbp}	.062 ***	(.017)
α_{euro}	.036 ***	(.006)	α_{gbp}	.064 ***	(.010)
$\beta_{euro,1}$	.932 ***	(.019)	$\beta_{euro,2}$	.114 ***	(.041)
$\beta_{gbp,1}$	-.002	(.010)	$\beta_{gbp,2}$	.765 ***	(.051)
ρ	.734 ***	(.009)			
θ_1	.800 ***	(.053)			
θ_2	.021 ***	(.005)			
P	-.002		P	.004	
P^2	.069		P^2	.056	
LB(6)	.048		LB(6)	8.580 *	
$LB(6)^2$	84.048 ***		$LB(6)^2$	50.506 ***	

Pair of returns: $R_{euro,t}$ and $R_{chf,t}$

	Euro Estimates			Swiss franc (chf) Estimates	
a_{euro}	.013	(.012)	a_{chf}	.019 **	(.009)
$b_{euro,1}$	-.042 ***	(.011)	$b_{euro,2}$	-.201 ***	(.014)
			$b_{chf,2}$	.154 ***	(.012)
d_{euro}	.069 ***	(.006)	d_{chf}	.011 **	(.006)
ω_{euro}	.029	(.022)	ω_{chf}	.078 **	(.033)
α_{euro}	.035 **	(.016)	α_{chf}	.056 ***	(.016)
$\beta_{euro,1}$	.934 ***	(.039)	$\beta_{euro,2}$	.315 ***	(.119)
$\beta_{chf,1}$	-		$\beta_{chf,2}$	.555 ***	(.150)
ρ	.901 ***	(.005)			
θ_1	.844 ***	(.024)			
θ_2	.041 ***	(.006)			
P	.011		P	.007	
P^2	.074		P^2	.071	
LB(6)	2.576		LB(6)	4.908	
$LB(6)^2$	94.841 ***		$LB(6)^2$	83.623 ***	

Note: The number in parentheses is the robust standard error suggested by White (1982). ***, ** and * indicate 1, 5 and 10 percent levels of significance, respectively. P and P^2 are the first order serial correlations of the standardized residual and the squared standardized residual, respectively. LB(6) and $LB(6)^2$ are the Ljung-Box test statistics with six lags for serial correlation in the standardized residual and the squared standardized residual, respectively.

Table 4

Dynamics of conditional correlation

4A. Results of ARMA(1,1) of order flow X_{euro}

	Estimates			
cons	.013	*	(.008)	
μ	.592	***	(.208)	
ξ	-.534	**	(.219)	$X_{euro,t} = \text{cons} + \mu X_{euro,t-1} + \xi \upsilon_{t-1} + \upsilon_t$
σ^2	.997	***	(.007)	$\upsilon_t \sim N(0,\sigma^2)$.

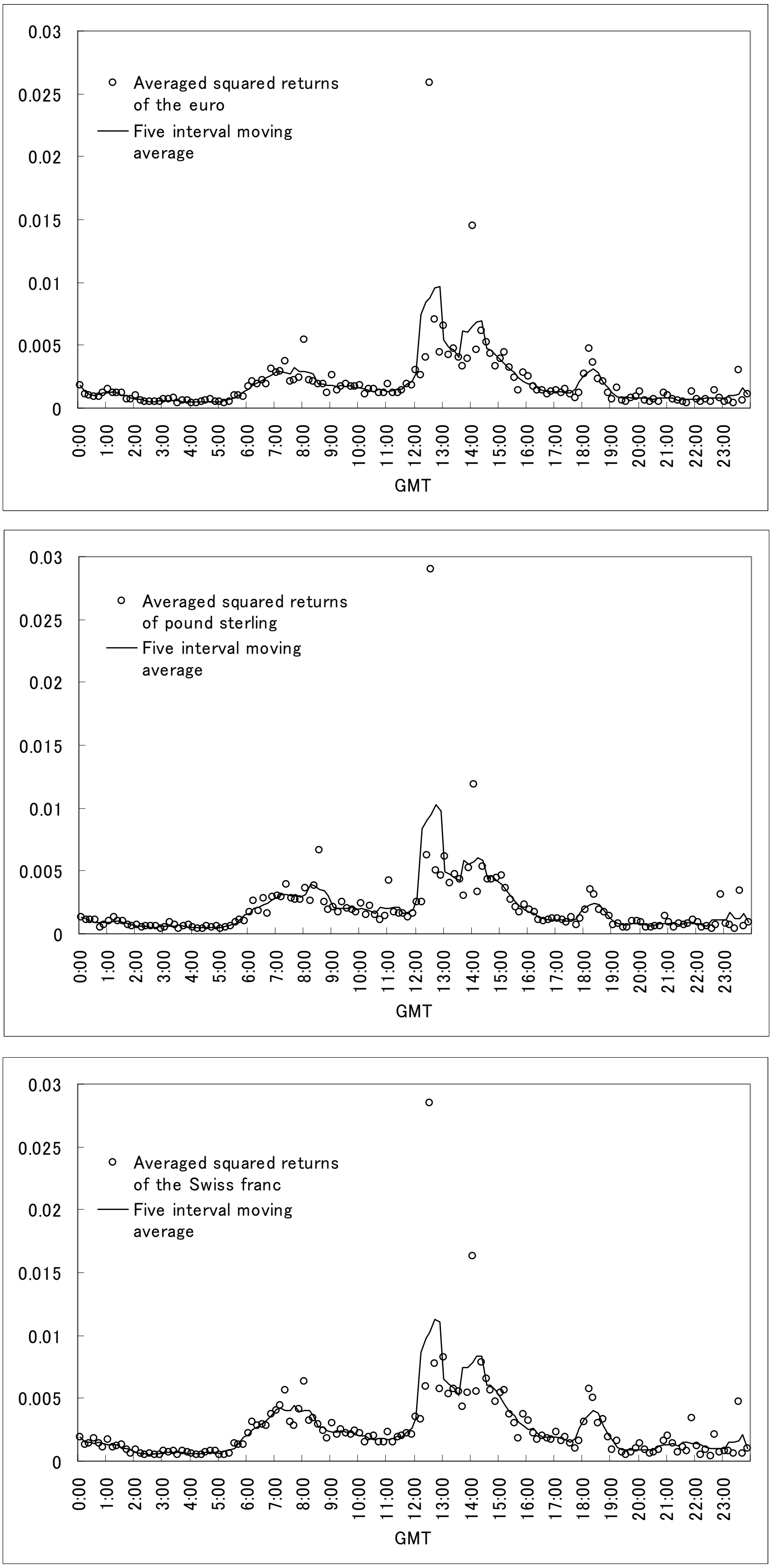
4B. Estimation of regression of conditional correlation

Cross correlation between the euro and the pound	Estimate			Cross correlation between the euro and the Swiss franc	Estimate		
τ	.09261	***	(.00311)	τ	.08693	***	(.00319)
γ_1	1.22397	***	(.01028)	γ_1	1.24181	***	(.01331)
γ_2	-.50334	***	(.01344)	γ_2	-.44797	***	(.01673)
γ_3	.19610	***	(.01234)	γ_3	.15542	***	(.01334)
γ_4	-.06519	***	(.01263)	γ_4	-.04891	***	(.00902)
γ_5	.02064	***	(.00807)				
λ_1	.00001		(.00056)	λ_1	.00103	*	(.00076)
λ_2	.00001		(.00056)	λ_2	-.00147	*	(.00096)
λ_3	-.00100	**	(.00057)	λ_3	-.00214	**	(.00094)
λ_4	-.00169	***	(.00058)	λ_4	-.00262	***	(.00099)
λ_5	-.00073		(.00060)	λ_5	-.00201	**	(.00094)
λ_6	-.00064		(.00056)	λ_6	-.00045		(.00084)
λ_7	-.00004		(.00057)	λ_7	.00073		(.00082)
λ_8	-.00108	**	(.00058)	λ_8	.00029		(.00084)
λ_9	-.00100	**	(.00055)	λ_9	-.00096		(.00088)
λ_{10}	-.00151	***	(.00063)	λ_{10}	-.00074		(.00093)
λ_{11}	-.00047		(.00056)	λ_{11}	-.00039		(.00091)
λ_{12}	-.00030		(.00058)	λ_{12}	.00171	***	(.00073)
λ_{13}	.00112	**	(.00053)	λ_{13}	.00243	***	(.00074)
λ_{14}	.00137	***	(.00052)	λ_{14}	.00218	***	(.00078)
λ_{15}	.00050		(.00053)	λ_{15}	.00161	**	(.00078)
λ_{16}	.00005		(.00052)	λ_{16}	.00091		(.00081)
λ_{17}	-.00038		(.00061)	λ_{17}	.00068		(.00080)
λ_{18}	.00063		(.00054)	λ_{18}	-.00005		(.00092)
λ_{19}	-.00150	***	(.00059)	λ_{19}	-.00365	***	(.00099)
λ_{20}	-.00152	***	(.00062)	λ_{20}	-.00339	***	(.00099)
λ_{21}	-.00165	***	(.00063)	λ_{21}	-.00525	***	(.00108)
λ_{22}	-.00139	**	(.00063)	λ_{22}	-.00431	***	(.00117)
λ_{23}	-.00168	***	(.00059)	λ_{23}	-.00265	***	(.00101)
δ	.00022	***	(.00004)	δ	.00020	***	(.00007)

Note: The number in parentheses in Table 4A is the robust standard error suggested by White (1982). The number in parentheses in Table 4B is the standard error calculated with the Newey and West variance-covariance matrix. ***, ** and * indicate 1, 5 and 10 percent levels of significance, respectively.

Figure 1

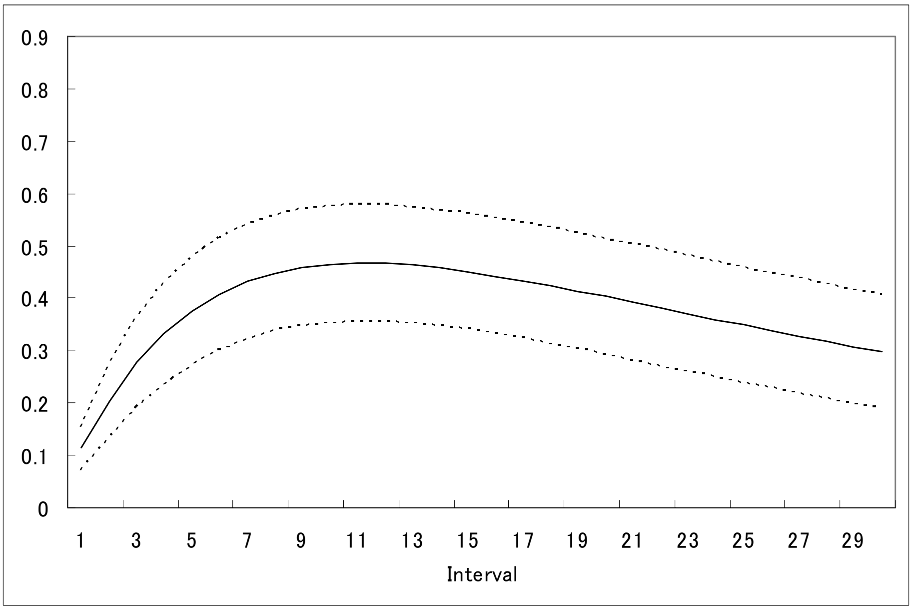
Seasonality of *second* moments of the euro, pound sterling and Swiss franc



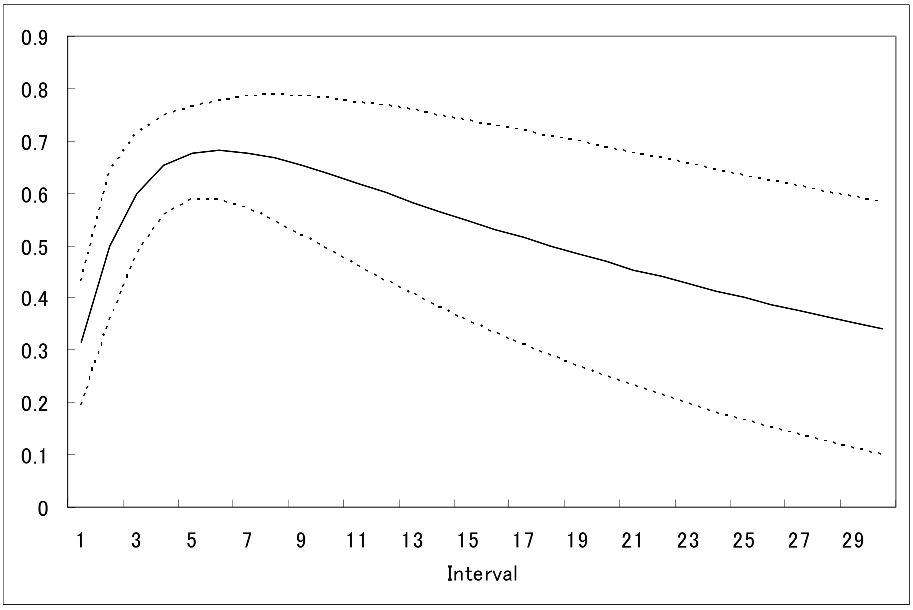
Note: The vertical axis shows the averaged second moments of the returns in each interval. The horizontal axis is Greenwich Mean Time (GMT).

Figure 2

Impulse response function responding to a shock in euro volatility



Series of responses of the pound volatility to a shock in euro volatility

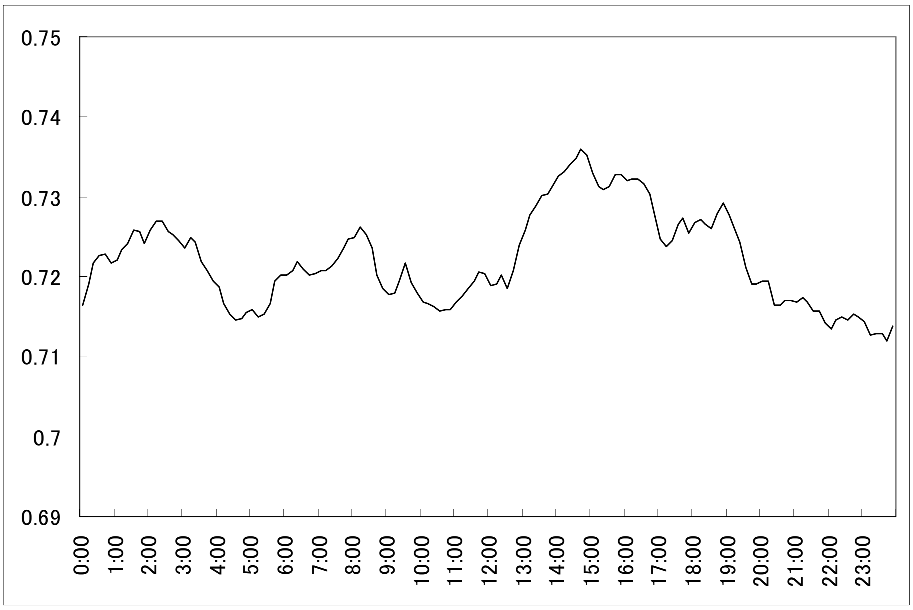


Series of responses of the Swiss franc volatility to a shock in euro volatility

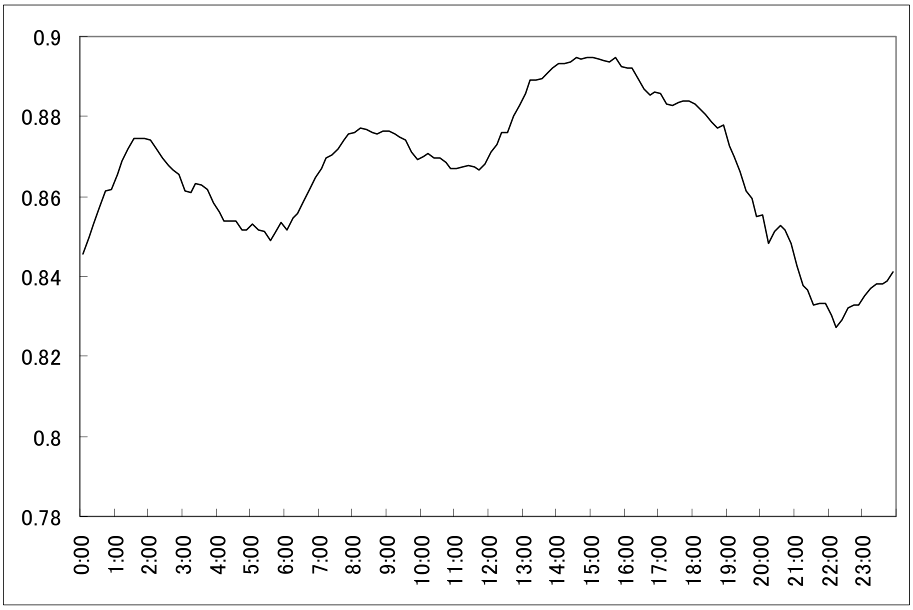
Note: The dotted line is the estimated two-standard error boundary. We obtained the standard errors by linear approximation (*see* Appendix). The horizontal axis shows each 10-minute interval (1 is one 10-minute interval).

Figure 3

Averaged cross correlation in each interval



Averaged cross correlation between the euro and pound sterling



Averaged cross correlation between the euro and Swiss franc

Note: The vertical axis shows the averaged cross correlation in each interval. The horizontal axis is Greenwich Mean Time (GMT).