International Transmission of Stock Market Movements

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Abstract

This paper investigates the international transmission mechanism of stock market movements by estimating a nine-market vector autoregression (VAR) system. Using simulated responses of the estimated VAR system, we (i) locate all the main channels of interactions among national stock markets, and (ii) trace out the dynamic responses of one market to innovations in another. Generally speaking, a substantial amount of multi-lateral interaction is detected among national stock markets. Innovations in the U.S. are rapidly transmitted to other markets in a clearly recognizable fashion, whereas no single foreign market can significantly explain the U.S. market movements. Also, the dynamic response pattern is found to be generally consistent with the notion of informationally efficient international stock markets.

I. Introduction

Since Grubel's work (1968), which expounded the benefits from international portfolio diversification, the relationship among national stock markets has been analyzed in a series of studies, such as Granger and Morgenstern (1970), Ripley (1973), Lessard (1974), (1976), Panton, Lessig, and Joy (1976), and, more recently, Hilliard (1979). Despite the divergent empirical methods used, these studies generally found that (i) correlations among returns to national stock markets are surprisingly low, and (ii) national factors play an important role in the return-generating process.[1] These findings were often cited as evidence supporting international, as opposed to purely domestic, diversification of investment portfolios. As noted, the previous literature was mainly concerned with showing that the interdependence of share price movements is much less pronounced among countries than within a country. Consequently, relatively little attention was paid to the structure of interdependence among national stock markets.

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[1] These empirical findings, however, were not unanimously confirmed by researchers. Agmon (1972), (1973), for example, found a substantial amount of relationship among the four stock markets in his sample, i.e., Germany, Japan, the U.K., and the U.S. Stock prices in non-U.S. countries were found to respond to changes in the U.S. prices with no significant lags on a monthly basis. The use of monthly data, however, would obscure any lags lasting but a few days.

Careful examination of international stock market movements in recent years suggests that there exists a substantial degree of interdependence among national stock markets. Furthermore, unexpected developments in international stock markets seem to have become important "news" events that influence domestic stock markets. To date, however, there exists no in-depth analysis of the interdependence structure of national stock markets. The purpose of this paper is to provide such an analysis with a special emphasis on the international transmission mechanism of stock market movements. Specifically, this paper addresses the following issues:

(i) How much of the movements in one stock market can be explained by innovations in other markets?

(ii) Does the U.S. stock market indeed influence other markets? Are there any markets whose movements are causally prior to those of other markets?

(iii) How rapidly are the price movements in one market transmitted to other markets?

In attempting to answer the above questions, we estimate a nine-market vector-autoregressive system using daily rates of return on the stock market indices from the period January 1980 through December 1985. We use daily return data to capture potential interactions, since a month or even a week may be long enough to obscure interactions that may last only for a few days. The nine markets included in this study are Australia, Canada, France, Germany, Hong Kong, Japan, Switzerland, the United Kingdom, and the United States.[2] The vector-autoregressive analysis (VAR, henceforth), which was developed by Sims (1980), estimates unrestricted reduced form equations that have uniform sets of the lagged dependent variables of every equation as regressors. The VAR thus estimates a dynamic simultaneous equation system, free of a priori restrictions on the structure of relationships. Since no restrictions are imposed on the structural relationships among variables, the VAR can be viewed as a flexible approximation to the reduced form of the correctly specified but unknown model of the actual economic structure. Considering that the large-scale structural models are very often misspecified, it seems to be appealing to use the VAR for the purpose of stylizing empirical regularities among time-series data.

Once our nine-market VAR system is estimated, we can trace out the dynamic responses of each of the nine markets to innovations in a particular market using the simulated responses of the estimated VAR system. In addition, the innovative accounting technique of the VAR allows us to measure the relative importance of each market in generating unexpected variations of returns to a particular market and thus to establish causal ordering among national stock markets. The empirical findings of our VAR analysis are thus expected to shed new light on the interdependence structure of national stock markets, in general, and

[2] The nine markets included in this study are among the world's largest stock markets in terms of capitalization value. These markets collectively account for about 93 percent of the world stock market index value (calculated by Morgan Stanley Capital International Perspective) as of the end of 1985. In addition, the nine markets coincide with those whose indices are reported by *The Wall Street Journal* on a daily basis.

the international transmission mechanism of stock market movements, in particular.

In interpreting empirical results of VAR analysis, we recognize that national stock markets are operating in diverse time zones with different opening and closing times, thereby making return observations nonsynchronous. In this paper, we tackle the problem of nonsynchronism by first carefully examining the structure of time differences, and then explicitly incorporating its implications into the interpretation of empirical results. To illustrate this point briefly, suppose that the German stock market is influenced by developments in the U.S. stock market. Considering that for a given calendar day the German stock market is closed before the U.S. market opens, the German market would not be able to respond to a U.S. shock in the same day; instead, it would respond to the U.S. shock with a one-day lag. On the other hand, if the U.S. market is influenced by the developments in the German market, the former should respond to a German shock in the same day in an efficient market. This is the case because the trading hours of the German market precede those of the U.S., providing the latter with an opportunity to react without delay. To recapitulate, despite the nonsynchronous nature of return data employed, we can interpret the results of VAR analysis based on the structure of time zone differences and therefrom obtain useful insights into the international transmission mechanism of stock market movements.

Our empirical results indicate that a substantial amount of multi-lateral interaction exists among national stock markets. As can be expected, the U.S. stock market turns out to be, by far, the most influential in the world. Innovations in the U.S. stock market are rapidly transmitted to other markets in a clearly recognizable pattern, whereas no single foreign market can significantly explain the U.S. market movements. The rather speedy transmission of a U.S. shock to other markets observed in this study generally supports the notion of informationally efficient international stock markets.

The organization of the paper is as follows. Section II reviews the vector autoregression methodology. Section III discusses data and a few related issues. The paper's main results are presented in Section IV. Section V offers a summary and concluding remarks.

II. The VAR Model

The VAR model examined includes nine variables that are daily rates of return to the nine major national stock markets. The VAR model is expressed as

$$Y(t) = C + \sum_{s=1}^{m} A(s)Y(t-s) + e(t) \,, \qquad (1)$$

where $Y(t)$ is a 9×1 column vector of daily rates of return of the nine stock markets, and C and $A(s)$ are, respectively, 9×1 and 9×9 matrices of coefficients, m is the lag length, and $e(t)$ is the 9×1 column vector of forecast errors of the best linear predictor of $Y(t)$ using all the past $Y(s)$. By construction, $e(t)$ is uncorrelated with all the past $Y(s)$. If this is combined with the fact that $e(t)$ is also a linear combination of current and past $Y(t)$, $e(t)$ is serially uncorrelated.

The i,jth component of $A(s)$ measures the direct effect that a change in the return to the jth market would have on the ith market in s periods. As can be seen from Equation (1), the right-hand side of each equation contains exactly the same terms, i.e., a constant, lagged value of each variable, and the error term.

Autoregressive systems such as (1), especially the coefficients of the regression equations containing complicated cross-equation feedbacks are difficult to describe intuitively. As shown by Sims (1980), it is better to analyze the system's reaction to typical random shocks or, equivalently, trace out the system's moving average representation. By successive substituting on the right-hand side of Equation (1), we can obtain a moving average representation as follows,

$$Y(t) = \sum_{s=0}^{\infty} B(s) e(t-s) , \tag{2}$$

which represents $Y(t)$ as a linear combination of current and past one-step-ahead forecast errors or "innovations."[3] The i,jth component of $B(s)$ shows the response of the ith market in s periods after a unit random shock in the jth market and none in other markets.[4]

Although $e(t)$ is serially uncorrelated by construction, the components of $e(t)$ may be contemporaneously correlated. In order to observe the distinct response patterns the VAR system may display, it is useful to transform the error terms. To achieve this, we choose a lower triangular matrix V and obtain the orthogonalized innovations u from $e = Vu$. It is noted that the transformed innovation $u(t)$ has an identity covariance matrix, such that $Eee' = S$ and $VV' = S$. Upon making an orthogonalized transformation to $e(t)$, Equation (2) can be rewritten as follows,

$$\begin{aligned} Y(t) &= \sum_{s=0}^{\infty} B(s) V u(t-s) \\ &= \sum_{s=0}^{\infty} C(s) u(t-s) , \end{aligned} \tag{3}$$

where $C(s) = B(s)V$. Then the i,jth component of $C(s)$ represents the impulse (or reflex) response of the ith market in s periods to a shock of one standard error in the jth market.[5] A detailed description of the triangular orthogonalization procedure is provided in the Appendix.

[3] Innovations $e(t)$ are defined as

$$e(t) = Y(t) - P[Y(t) \mid Y(t-1), Y(t-2), \ldots] ,$$

where P denotes the linear least squares projection of $Y(t)$ in the space spanned by $[Y(t-1), Y(t-2), \ldots]$. As will be seen shortly, the moving average representation of (2) enables us to trace out the reactions of international stock markets to news, $e(t)$, in the form of unexpected developments in a national stock market.

[4] The i,jth component of $B(s)$ represents the conditional expectation at time t of changes of the ith stock market returns in s periods caused by a unit change in the jth market, conditional on the information available at time t.

[5] To be consistent with the historical correlation pattern of innovations, we introduce a contemporaneous shock in each equation that is equal to the corresponding element in the jth column of matrix V when we introduce one standard deviation shock in the jth market. See the Appendix for a detailed exposition of this point.

Another advantage of using orthogonalized innovation is that we can also allocate the variance of each element in Y to sources in elements of u, since u is serially and contemporaneously uncorrelated. The orthogonalization provides the quantity, $\Sigma_{s=0}^{T} C_{ij}^{2}(s)$, which is the component of forecast error variance in the $T+1$ step ahead forecast of Y_i, which is accounted for by innovations in Y_j. This decomposition of forecast error variance provides a measure of the overall relative importance of the markets in generating the fluctuations in stock returns in their own and other markets.[6]

If one stock market is causally prior to other markets in the sense that the price movements of the market affect subsequent price movements in other markets, but are not affected by price movements of other markets in earlier periods, then the forecast errors of future returns of this influential market should be mostly accounted for by its own innovations, and should not be explained substantially by the innovations of the other markets. The innovations of the influential market should also explain a substantial fraction of the forecast error variances of other markets.

III. Description of the Data

The data base used in this study consists of time series of daily stock market indices at closing time, in terms of local currency units, of the world's nine major stock markets, as calculated by Morgan Stanley Capital International Perspective, Geneva. It covers the period December 31, 1979, through December 20, 1985, with a total of 1,560 observations. These stock market indices are transformed to daily rates of return, which are then used in our VAR analysis. Potential problems associated with any nonstationarity in the original stock market indices can be alleviated by using the transformed data. The stock market indices used in this study do not double-count those stocks multiple-listed on foreign stock exchanges. Consequently, any observed interdependence among stock markets cannot be attributed to the multiple listings.

Given that national stock markets are generally operating in different time zones with different opening and closing times, their rates of return on a given calendar day may, in fact, represent the returns realized over different real time periods. For the purpose of interpreting the empirical results later on, it is important to know the operating hours of one market relative to other markets in a real time scale. This information is provided in Table 1, which shows the opening and closing times of the major stock exchanges in New York time.

As can be seen in Table 1, all of the Asian-Pacific exchanges as well as two European exchanges, i.e., Paris and Frankfurt, are closed when the New York Stock Exchange (NYSE) opens for the day. On the other hand, the London and Zurich exchanges operate from 4:30 a.m. to 10:30 a.m. by New York time, closing half an hour after the NYSE has opened. When the European exchanges open for the day, all of the Asian-Pacific exchanges are closed. The Toronto Stock Exchange, which is the last, along with the NYSE, to open for the day, operates concurrently with the NYSE.

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[6] For a more detailed description of the VAR model, refer to Sims (1980).

TABLE 1

Opening and Closing Times of Major Stock Exchanges in New York Time

Exchange	Opening—Closing Time[a]	
Australia	*8:00 p.m.–	1:00 a.m.
Japan	*8:00 p.m.–	2:00 a.m.
Hong Kong	*10:00 p.m.–	3:30 a.m.
U.K.	4:30 a.m.–	10:30 a.m.
Switzerland	4:30 a.m.–	10:30 a.m.
France	5:30 a.m.–	8:30 a.m.
Germany	5:30 a.m.–	7:00 a.m.
Canada	10:00 a.m.–	4:00 p.m.
U.S.A.	10:00 a.m.–	4:00 p.m.

[a] These times are as of December 1985. Asterisk (*) denotes previous day in New York time.

IV. Empirical Results

In this paper, the lag length of VAR is chosen to be 15 trading days. We test a VAR with 15 lags in each variable against one with 20 lags, and we cannot reject the hypothesis that the restriction of excluding 16 through 20 lags holds, at the usual 5-percent significance level. Neither can we reject the hypothesis that all the coefficients of lags 21 through 25 periods are zero at the 5-percent significance level. All in all, there seems to be little, if any, feedback to the current stock market returns from returns lagged more than 15 days. Thus, all the statistical results presented below are based on the VAR with a lag of 15 trading days, which is equivalent to three weeks.[7]

A. Preliminary Discussion

Table 2 reports the contemporaneous correlations of the residual returns among the nine national stock markets. The residuals, or innovations, represent abnormal stock market returns that were not predicted on the basis of all the information reflected in past returns. The contemporaneous correlations of the residual returns reflect the degree to which new information producing an abnormal return in one market is shared by the other markets in the same calendar day.

Table 2 shows that, in general, the intra-regional pairwise correlations tend to be higher than the inter-regional correlations. For example, the U.S./Canada exhibits the highest correlation, followed by Germany/Switzerland, whereas the correlations for such pairs as Canada/Japan and France/Hong Kong are close to zero. This pattern of contemporaneous correlations is consistent with what we expect from the structure of time zone differences between pairs of markets. The correlation pattern also may reflect the degree of economic integration between countries. This is so because the more integrated two economies are, the more strongly the stock market movements in one country would be correlated to those in another country. The unusually high correlation of U.S./Canada seems to attest to this factor.

[7] Computer processing time with a large data set imposes another restriction on the choice of the lag length. In our nine-market VAR system, for each additional lag, the number of coefficients to be estimated increases by 81.

In line with the general observations made above, the conteporaneous correlations of the U.S. with the Asian-Pacific and European markets, with the exception of the U.K., are all low. Considering that the trading hours of these markets precede those of the U.S., development in these markets do not appear to have much impact on the U.S. market. The relatively high correlation observed between the U.S. and the U.K. may reflect, at least in part, the fact that the two markets simultaneously operate for half an hour before the U.K. market closes. To recapitulate, a foreign market's correlation with the U.S. tends to get smaller the farther away the market is from the U.S. This particular pattern of contemporaneous correlations seems to suggest that the U.S. stock market influences other stock markets. If the U.S. market were to be influenced, say, by the Japanese market, which closes before the U.S. market opens, then the U.S. market could have responded to the Japanese developments in the same day. This, in turn, would have resulted in a higher contemporaneous correlation between the two markets.

TABLE 2

The Correlation Matrix of Residual Returns[a]

	AU	CA	FR	GE	HK	JA	SW	UK	US
Australia (AU)	1.000	0.045	0.068	0.050	0.124	0.127	0.069	0.051	0.035
Canada (CA)		1.000	0.029	0.060	0.062	0.005	0.105	0.205	0.673
France (FR)			1.000	0.078	−0.006	0.095	0.114	0.086	0.022
Germany (GE)				1.000	0.086	0.149	0.279	0.136	0.053
Hong Kong (HK)					1.000	0.079	0.040	0.074	0.088
Japan (JA)						1.000	0.188	0.104	0.020
Switzerland (SW)							1.000	0 129	0.083
U.K. (UK)								1.000	0.176
U.S.A. (US)									1.000

[a] Each entry in the table represents the contemporaneous correlation coefficient of the residual returns between a pair of countries, net of expected returns that are estimated from the nine-market vector-autoregressive system using daily returns from the period 1980 1–1985.12.

B. Accounting National Stock Market Innovations

As previously mentioned, the forecast error variance of each stock market can be allocated to sources by using orthogonalized innovations. For each market, the orthogonalization procedure provides the component of forecast error variance that is accounted for by innovations in each of the nine markets. Table 3 provides the decomposition of 5-day, 10-day, and 20-day ahead forecasts of stock market returns into fractions that are accounted for by innovations of different markets.[8] Table 3 can thus be viewed as a summary that is useful in identifying the main channels of influence in the nine-market dynamic system. The more salient features of Table 3 are discussed below.

[8] In this study, the orthogonalization is ordered as the U.S., the U.K., Switzerland, Japan, Hong Kong, Germany, France, Canada, and Australia. When the different innovations are correlated, the error variance decomposition could be sensitive to the order of variables for orthogonalization. To determine the exogeneity of U.S. stock market returns, however, any ordering that puts the U.S. at the top would suffice (See Doan and Litterman (1981), pp. 11–18). When we change the order of variables, the U.S. still emerges as the dominant market.

Table 3 indicates that no national stock market is exogenous in that a market's own innovations fully account for its variance.[9] On the contrary, a substantial amount of interaction is detected among national stock markets. At the horizon of 20 days, for example, the percentage of error variance of a national stock market attributable to collective innovations in foreign stock markets ranges from 11.02 percent for the U.S. to 52.02 percent for Canada, with the average of 25.93 percent.

The results in Table 3 also indicate that the U.S. stock market is the most influential in the world. While no single foreign market can explain more than 2 percent of the U.S. error variance, the U.S. explains 6.43 percent (for Hong Kong) through 42.03 percent (for Canada) of the foreign market error variances, with the average of 16.78 percent. This U.S. average value is compared with 2.56 percent and 2.15 percent, respectively, for Switzerland and the U.K., the two relatively more influential foreign markets. Also, the U.S. innovations account for about 89 percent of its own variance. No other market is so nearly exogeneous in the sense defined above.

Switzerland turns out to be the most interactive market. Innovations in the Swiss market have repercussions in every other market and, at the same time, innovations in every other market are fed into the Swiss market. This highly interactive nature of the Swiss stock market seems to reflect a high degree of integration of the Swiss economy with the world economy in general.

The pattern of interactions among Australia, Canada, Hong Kong, and the U.K. revealed in Table 3 suggests that a British Commonwealth factor may be present. Innovations in the Canadian, Hong Kong, and U.K. markets collectively account for nearly 10 percent of the Australian variance. And about 6 percent of the Canadian variance is explained by innovations in Australia, Hong Kong, and the U.K.

Table 3 also provides evidence that the Japanese stock market, which is comparable to the U.S. stock market in terms of capitalization value, acts like a follower in international stock markets. Innovations in the Japanese market fail to explain any substantial part of error variances of other markets. But the U.S. as well as the European markets, especially Switzerland and U.K., exert substantial influence on the Japanese market. The European innovations collectively account for about 9 percent of the Japanese variance, whereas the U.S. innovations account for about 11 percent.

C. Dynamic Response Pattern

To obtain additional insight into the mechanism of international transmission of stock market movements, we now examine the pattern of dynamic responses of each of the nine markets to innovations in a particular market using the simulated responses of the estimated VAR system. To conserve space, we concentrate on the responses of each of the nine markets to a shock in the U.S. market. Table 4 provides normalized impulse responses of the nine markets to a

[9] When we conduct the Granger (1969) exogeneity test, the hypothesis that the U.S. or any single market is exogenous to other markets is strongly rejected at the 5-percent significance level. The hypothesis that the U.S. and Canada, as a block, are exogenous also is rejected at the 5-percent significance level.

TABLE 3
Accounting National Stock Market Innovations[a]

Market Explained	Horizon (in days)	By Innovations in AU	CA	FR	GE	HK	JA	SW	UK	US	FM[b]
Australia	5	73.89	2.80	1.16	0.31	1 17	1.13	0.60	3.50	15.44	26.11
	10	72.07	3.24	1.24	0.45	1 64	1.43	0 68	3.94	15.31	27 93
	20	70 05	3.49	1 70	0.82	2.06	1.46	1.48	4.03	14.89	29.95
Canada	5	0.24	51.74	0.06	0.24	0.39	0.30	0.57	0.85	45.59	48.26
	10	1.03	49.92	0.29	0.28	1.13	0.49	1.40	1.43	44.04	50.08
	20	1.94	47.98	0.71	0.74	1.60	0.85	2.09	2.05	42.03	52.08
France	5	0.15	0.44	82.38	0.33	0.97	1.11	1.07	0.66	12.89	17.62
	10	0.47	0.53	80.02	0.44	1.64	1.24	1.72	1.11	12 83	19.98
	20	0.97	0.79	77.81	0.77	1.97	1.36	2.04	1.57	12.72	22.19
Germany	5	0.48	0.41	0.11	75.64	0.78	0.85	5.89	1.59	14.25	24.36
	10	0.74	0.59	0.57	73.41	0.89	1.39	6.79	1.81	13.80	26.59
	20	0.83	0.88	0.81	71.98	1.17	1.65	6.80	2.01	13.88	28.02
Hong Kong	5	0.16	0.40	0.31	0.57	90.36	0.55	0.31	1.05	6.28	9.64
	10	0.34	1.20	0.38	0.88	87.38	0.96	0.93	1.70	6.23	12.62
	20	0.84	1.43	0.67	1.07	84.49	1.46	1.31	2.30	6.43	15.51
Japan	5	0.70	0.43	0.24	0.31	0.82	81.15	3.14	2.54	10.68	18.85
	10	0.88	0.57	0.71	0.70	1.22	78.88	3.55	2.57	10.92	21.12
	20	1.36	0.93	1.26	1.03	1.67	76.22	3.62	2.87	11.04	23.78
Switzerland	5	0.27	0.58	0.47	0.62	0.47	0.27	76.23	1.14	19.93	23.77
	10	0.45	0.63	1.40	0.78	0.69	0.74	73.89	1.35	20.07	26.11
	20	0.97	1.65	1.83	1.28	1.02	1.24	71.13	1.38	19.49	28.87
U.K.	5	0.39	1.01	0.16	0 11	0.44	0.22	0.57	82.70	14.40	17.30
	10	0.51	1.25	0.75	0.26	0.98	0.81	0.94	80.45	14.06	19.55
	20	0.88	1.66	1.45	0.66	1.20	1.38	1.08	77.94	13.76	22.06
U.S.A.	5	0.59	1.19	0.18	0.15	0.84	0.37	0.34	0.07	96.27	3.73
	10	0.71	1.70	0.26	0.38	1.06	0.68	1.49	0.56	93.16	6.84
	20	1.30	2.24	1.00	0.76	1 32	1.28	2.09	1.02	88.98	11.02

[a] Each entry in the table denotes the percentage of forecast error variance of the left-hand side market explained by the market at the top.
[b] Each entry in the last column, FM, of the table denotes the percentage of forecast error variance of the left-hand side market explained collectively by the "foreign" markets.

typical shock, i.e., positive residuals of one standard deviation unit, in the U.S. These normalized impulse responses are the estimates of moving average coefficients in Equation (3) divided by their standard errors.[10] To facilitate the interpretation of Table 4, we plot the time paths of the normalized impulse responses of the nine markets to a U.S. shock in Figure 1.[11]

As can be seen from examination of Figure 1, innovations in the U.S. stock market are rapidly transmitted to all the other markets. All the European and Asian-Pacific markets respond to the U.S. shock most dramatically on day 1 and, thereafter, the responses rapidly taper off. Take the French response, for instance. Table 4 shows that the French impulse response to a U.S. shock is 0.40

[10] The normalization procedure is necessary due to different variations of returns across stock markets. This procedure also makes it easy to interpret the empirical results, as the normalized responses can be taken as the correlation coefficients.

[11] Impulse responses of the VAR system to shocks in other markets are available from the authors upon request.

on day 1, followed by -0.05 on day 2, and -0.01 on day 3. Since these foreign markets are either closed or about to be closed when the U.S. market opens, they are expected to react to the U.S. shock with a one-day lag. This is exactly what we observe in Figure 1. It also can be seen from Figure 1 that much of the adjustment of foreign stock prices to the U.S. shock is completed by day 2.

As can be seen from Table 4, the impulse response of the Canadian market to a U.S. shock is 0.67 on day 0, followed by 0.21 on day 1, and 0.04 on day 2. This implies that, unlike other markets, the Canadian market responds most strongly to the U.S. shock on day 0 when the U.S. shock occurs, and most of the adjustments are completed by day 1. This result may reflect a high degree of economic and financial integration and the free flow of information between the two countries, as well as the concurrent operation of their stock markets. To some extent, the U.K. market also reacts to the U.S. shock without lag. Because the two markets operate concurrently for half an hour a day, this result is as expected. Unlike other markets, the U.K. seems to overreact somewhat to the U.S. shock on days 0 and 1, which is subsequently corrected by a negative reaction on day 2.

Further examination of Figure 1 reveals some interesting regional patterns. As can be seen from the second column of Figure 1, the three continental European markets, i.e., France, Germany, and Switzerland, respond to a U.S. shock in an almost identical fashion. They accommodate most of the U.S. shock on day 1. The absence of noticeable responses beyond day 1 indicates that these European markets are highly efficient in processing international news. In contrast, the third column of Figure 1 indicates that the Asian-Pacific markets, especially Australia and Japan, are somewhat sluggish in their response to a U.S. shock; these markets continue to react noticeably through day 2.

Considering that both the Australian and Japanese markets are influenced by the U.K. as well as U.S. markets, these seemingly sluggish responses are likely to reflect the reactions of these markets to the (unpredicted) U.K. reaction to the U.S. shock, rather than market inefficiency. Because Australia and Japan are situated between the U.S. and U.K. in terms of time zone, investors in these two countries cannot observe the British reaction to the U.S. shock on day 1 while their national stock markets are still in session. In other words, the Australian and Japanese markets respond to a U.S. shock on day 1, without knowing exactly how the U.K. market may respond to the U.S. shock. In consequence, if the subsequently observed British reaction to the U.S. shock contains surprise, the Australian and Japanese markets would respond on day 2 to this indirect U.S. shock transmitted via the U.K. market. Granting that these "reactions to reactions" may last for a few days following the original shock, the market efficiency would require that much of the responses to a shock should be completed in a few days.[12]

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[12] This view seems to be supported when we examine the patterns of Australian and Japanese reactions to a U.K. shock that, unlike a U.S. shock, elicits little or no reaction to the indirect shock fed via a second market. Both the Australian and Japanese markets essentially complete their reactions to a U.K. shock by day 1, with no further noticeable responses. Given the time zone difference between these two countries and the U.K., the observed response patterns are fully consistent with the market efficiency.

In view of our finding that many of the responses are completed in about two days after a shock, the pattern of impulse responses emerging from the VAR analysis seems to be broadly consistent with the notion of informationally efficient international stock markets. This implies that it would be difficult to earn unusual profits by investing in a particular market based on the observed developments in other markets. Finally, the leading role of the U.S. in the world stock market is corroborated when the response pattern to a U.S. shock is compared with that to a U.K. shock. Unlike the case of a U.S. shock, the reaction of other markets to a U.K. shock is found to be relatively weak. As previously mentioned, however, a U.K. shock seems to have material influences on the Australian and Japanese markets.

TABLE 4

Impulse Responses to the Unit Shock in the U.S. Market[a]

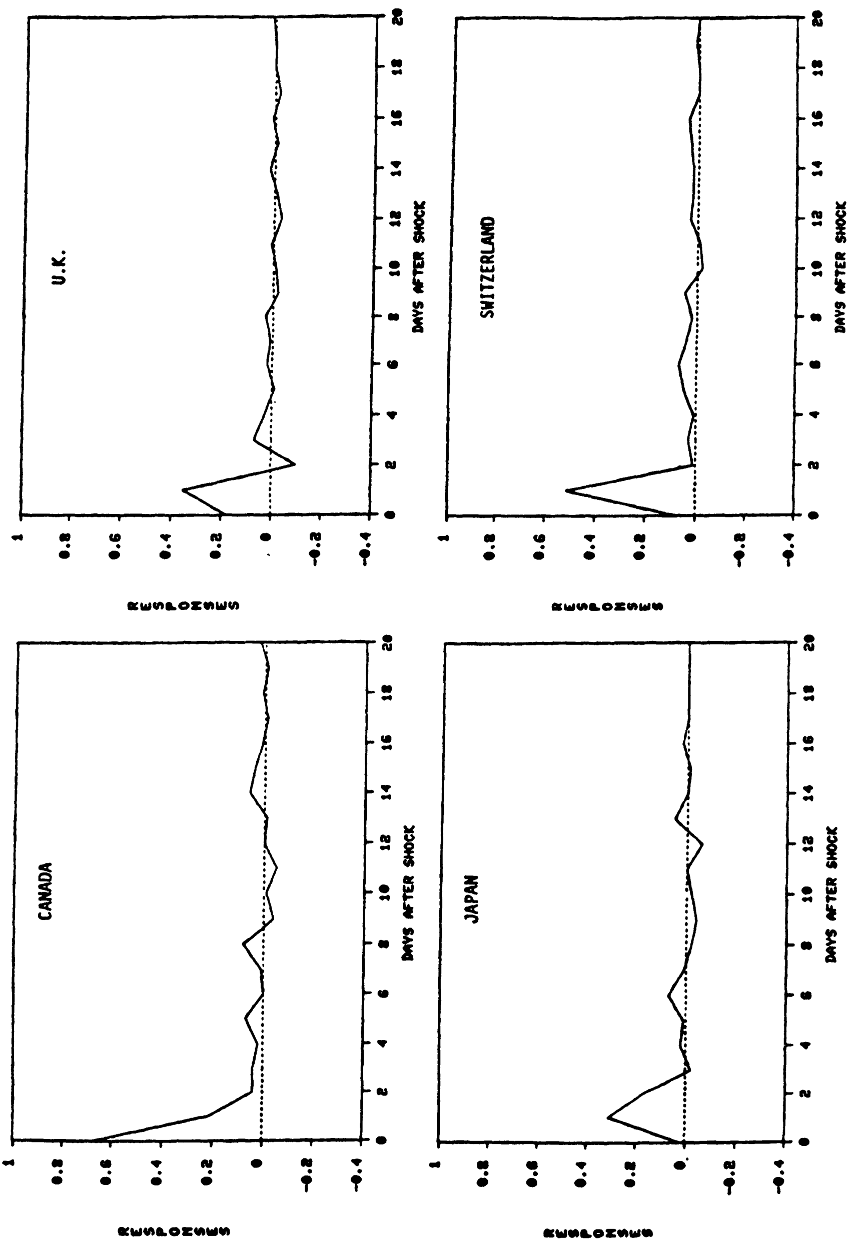
*i*th Day after Shock	Impulse Responses in								
	AU	CA	FR	GE	HK	JA	SW	UK	US
0	0.04	0.67	0.02	0.05	0.09	0.02	0.08	0.18	1.00
1	0.41	0 21	0.40	0 41	0.22	0 31	0.51	0.35	0 08
2	0 18	0.04	−0 05	−0 04	0.08	0.17	0.01	−0.10	0.04
3	0.05	0.04	−0.01	0.04	0.03	−0.02	0.03	0.07	−0.01
4	0 08	0 02	0.04	0.04	0.06	0.02	0.01	0.03	−0 02
5	0 06	0.07	0 00	0 02	0.01	0 01	0.05	−0 01	−0.02
6	−0.02	0 00	0.05	0.02	−0.01	0 07	0.07	0.02	0.00
7	0.00	0.01	0.03	0.02	−0.01	0.01	0.04	0.01	−0 04
8	0 03	0 08	0.01	−0.01	0.00	−0 02	0 02	0 03	0.03
9	0.01	−0.04	0 04	0.00	−0.04	−0 04	0.05	−0.02	−0.02
10	−0.01	−0 01	0 03	0 02	−0.01	−0.02	−0.02	−0.01	0.01
11	0.02	−0.05	0.01	0 04	−0.03	0.00	−0.01	0.01	−0 04
12	−0 01	0 00	−0 05	0 00	0 00	−0 06	0.03	−0.03	0.00
13	0.02	−0.01	0 01	−0.03	−0.03	0.05	0 02	−0.01	0 00
14	0 03	0.06	0.01	0.03	0.03	0.00	0.02	0.02	0.00
15	−0.01	0.04	0 01	0 05	0.05	−0.01	0.03	−0.01	0.02
16	0 01	0.01	0 04	−0.01	0 02	0 02	0 04	0 01	0.00
17	0 01	−0 01	0.01	−0 02	−0 01	0 00	0 00	−0.02	0 00
18	−0.01	0 01	0.00	0 00	−0 01	0 00	0.00	0.00	0.00
19	0 01	−0 01	0 01	0.00	0.01	0 00	0 01	0.00	−0.01
20	0 01	0 02	0 01	−0 02	0 00	0.00	0.00	0 01	0.01

[a] The *i,j*th entry in this table represents the normalized impulse response of the *j*th (column) market on the *i*th day (row) to the unit shock in the U S market These entries are the estimates of moving average coefficients of the VAR system divided by their standard errors

V. Summary and Concluding Remarks

In this paper, nine time series of daily stock market returns were interpreted via the vector autoregression (VAR) analysis in order to obtain insights into the interdependence structure of major national stock markets. Emphasis was on understanding the mechanism by which innovations in one stock market are transmitted to other markets over time. Since no prior restriction is imposed, the VAR analysis enables us to locate all the main channels of transmission via simulated responses.

Since national stock markets operate in diverse time zones with the result


U.K.
CANADA
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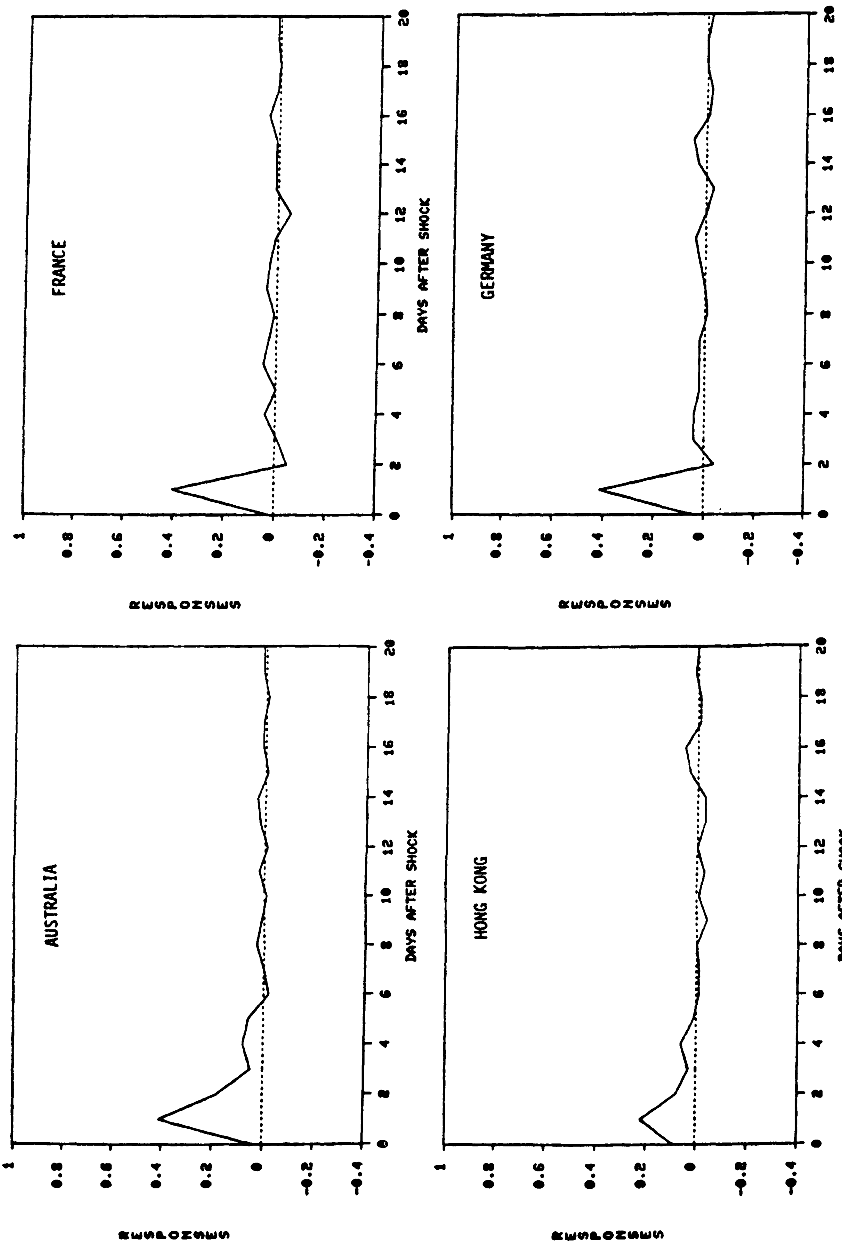

FIGURE 1
Time Paths of Impulse Responses to a U.S. Shock

that return observations are nonsynchronous, we carefully examined the structure of time differences and explicitly took into consideration its implications in interpreting empirical results of VAR analysis. Our evidence indicates that a substantial amount of interdependence exists among national stock markets. At the 20-day horizon, for example, innovations in foreign markets collectively account for about 26 percent of the error variance of a national stock market on the average. Moreover, the U.S. stock market is found to be, by far, the most influential market in the world. No national stock market is nearly as influential as the U.S. in terms of its capability of accounting for the error variances of other markets. This may reflect the dominant position of the U.S. in the world economy, which probably makes the country the most important producer of information affecting the world stock market.

We analyzed the dynamic responses of each of the nine markets to innovations in a particular market, using the simulated responses of the estimated VAR system. Against U.S. innovations, all the European and Asian-Pacific markets responded most strongly with a one-day lag and, thereafter, the responses tapered off rapidly. We find that most of the responses to a shock are completed within two days. The pattern of impulse responses emerging from the VAR analysis, therefore, generally supports the notion of informationally efficient international stock markets.

Appendix: VAR Methodology

Using a simple example, this appendix describes the ''triangular'' orthogonalization procedure employed in our VAR analysis and the nature of the shock introduced to a variable to elicit impulse responses from other variables. We begin with the moving average representation of the VAR system,

$$\text{(A.1)} \qquad Y(t) = \sum_{s=0}^{\infty} B(s)e(t-s) = \sum_{s=0}^{\infty} B(s)Vu(t-s) ,$$

where, as previously defined, V is a lower triangular matrix. If we apply the orthogonalization procedure, $e = Vu$, to a simple case of three variables, we obtain

$$\text{(A.2)} \qquad \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} V_{11} & 0 & 0 \\ V_{21} & V_{22} & 0 \\ V_{31} & V_{32} & V_{33} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} .$$

Let us now introduce a unit shock to the first variable, i.e., $[u_1 \ u_2 \ u_3]' = [1 \ 0 \ 0]'$. Then, (A.2) becomes

$$\text{(A.3)} \qquad \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} V_{11} \\ V_{21} \\ V_{31} \end{bmatrix} .$$

This result shows that each of the three variables is subject to a shock. To obtain a better understanding of the nature of these shocks, we apply the relationship $VV' = S(= Eee')$ to our three-variable case,

$$(A.4)\quad \begin{bmatrix} V_{11} & 0 & 0 \\ V_{21} & V_{22} & 0 \\ V_{31} & V_{32} & V_{33} \end{bmatrix} \begin{bmatrix} V_{11} & V_{21} & V_{31} \\ 0 & V_{22} & V_{32} \\ 0 & 0 & V_{33} \end{bmatrix} = \begin{bmatrix} \sigma_1^2 & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_2^2 & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_3^2 \end{bmatrix}.$$

From (A.4), it can be shown that $V_{11} = \sigma_1$, $V_{21} = \sigma_2\rho_{12}$, and $V_{31} = \sigma_3\rho_{13}$. Consequently, (A.3) can be rewritten as

$$(A.5)\quad \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} \sigma_1 \\ \sigma_2\rho_{12} \\ \sigma_3\rho_{13} \end{bmatrix},$$

which shows the exact nature of the shocks. As shown in (A.5), when the first variable is subject to a "typical" shock, which is equal in magnitude to one standard error of the first variable, each of the remaining variables is also subject to a shock that is equal to its own (unit) standard error multiplied by its correlation with the first variable. By considering "contemporaneous" shocks to other variables, the VAR method can reproduce the "historical" pattern of interactions among variables.

For a unit shock to the second variable, i.e., $[u_1\ u_2\ u_3]' = [0\ 1\ 0]'$, (A.2) becomes

$$(A.6)\quad \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} 0 \\ V_{22} \\ V_{32} \end{bmatrix} = \begin{bmatrix} 0 \\ \sigma_2\left(1-\rho_{12}^2\right)^{1/2} \\ \sigma_3\left(\rho_{23}-\rho_{12}\rho_{13}\right)\Big/\left(1-\rho_{12}^2\right)^{1/2} \end{bmatrix}.$$

Analysis of a shock to the third variable is left to readers.

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