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Behavioral foreign exchange rates

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BEHAVIORAL FOREIGN EXCHANGE RATES

by

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A Dissertation Presented in Partial Fulfillment

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ABSTRACT

The foreign exchange market is one of the most active financial markets. The sheer volume of trade in the foreign exchange market has captured the attention of many researchers. Since exchange rates began to float in 1973, there has been much empirical work on exchange rate behavior. The results from previous studies appear to be somewhat sensitive to econometric techniques employed. Thus, the correct statistical characterization of exchange rate behavior remains an open question.

Chapter 2 examines time-series behavior of monthly real exchange rates. The results show that real exchange rates do not follow a pure random walk process. Changes in monthly real exchange rates exhibit positive first-order autocorrelations at lower lags up to four-year horizons. Using the Beveridge-Nelson decomposition technique, all currencies allow the decomposition into permanent and transitory components. Further analysis implies that on average the transitory components account for more than half of the monthly variance of real exchange rates. Therefore, real exchange rates may be well represented by the sum of random walk and mean-reverting processes. The mean-reverting behavior is consistent with the assumptions underlying the purchasing power parity hypothesis and Dornbusch's overshooting exchange rate model.

Chapter 3 examines statistical properties of percentage changes in daily spot rates and their fundamental and non-fundamental components. The analysis shows that distributions of changes in spot rates vary over time due to changes in the variance of

the fundamental component. The appraisal of the non-fundamental component implies temporary deviations from long-run equilibrium exchange rates. I propose to model spot rate changes as an AR(1) process with GARCH(1,1) errors. The model is able to explain non-stationary variances for all currencies studied.

Chapter 4 examines foreign exchange market efficiency using relative strength investment strategies. The study documents significant positive returns from a trading strategy that buys as value of a currency rises and sells as the currency value falls. The positive returns persist even after incorporating interest rate differentials but disappear when a constant currency risk premium is added to the model. The findings suggest that excess returns from the trading strategies are the result of compensation for risk, not that of market inefficiency.

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CHAPTER 1

INTRODUCTION

Since the system of floating exchange rates began in 1973, studies of exchange rate behavior have become one of the most active areas of economic research. Academia and policymakers alike believed that exchange rates would adjust according to relative prices and, as such, the purchasing power parity hypothesis (PPP) would provide a close approximation of exchange rate movements (Koedijk (1998)).

Formal econometric tests in the early 1980s failed to reject the unit-root hypothesis for real exchange rates and the hypothesis of no-cointegration between nominal exchange rates and relative prices (Lothian (1998)). Researchers concluded that real exchange rates could be characterized as random walks and thus PPP did not seem to hold. An alternate hypothesis suggests that nominal exchange rates fluctuated more excessively than relative price levels, causing their relationship to drift apart (see, for example, Rogoff (1996) for a review of real exchange rate literature).

On the other hand, recent studies, such as Lothian and Taylor (1996) and Lothian (1998), document that there are significant mean-reverting components in real exchange rates. They find evidence supporting PPP and suggest that PPP is still a useful approximation to exchange rate behavior.

Chapter 2 addresses the question: what is a process best describes the time-series behavior of real exchange rates during the post-Bretton Woods period? Understanding real exchange rates provides a useful guide to the underlying process determining nominal exchange rates and helps creating exchange rate models that produce satisfactory empirical performance. Unlike previous real exchange rate studies, Chapter 2 uses a variance ratio test of Lo and MacKinlay (1988) together with the Beveridge and Nelson (1981) decomposition technique to examine monthly real exchange rates. The results suggest that real exchange rates exhibit mean reverting behavior and that PPP is still a useful building block in exchange rate modeling.

Having established that PPP is a useful approximation of exchange rate behavior, I turn my attention to the statistical properties of nominal exchange rates. Many studies of the underlying distribution of exchange rates suggest that high-frequency exchange rates exhibit leptokurtosis resulting from non-stationary mean and variance (see, for example, Boothe and Glassman (1987) and Hsieh (1988)).

No conclusive agreement about the distribution that best characterizes exchange rates has been reached. The search for a proper statistical distribution continues. Chapter 3 follows this research avenue. This chapter addresses three questions. (1) What are the statistical properties of daily exchange rates? (2) How could these statistical properties be reconciled with the Efficient Markets Hypothesis? And, (3) what would be a proper statistical model to describe exchange rates?

Unlike previous studies, I propose to separate exchange rates into fundamental (permanent) and non-fundamental (transitory) components and examine statistical properties of both components as well as the observed series. Then, I provide a discussion pertaining to two market efficiency views: (1) exchange rates are drawn from a normal distribution with non-stationary variance and (2) exchange rates contain discrete jumps. I also attempt to identify a class of data-generating processes based on the statistical properties previously analyzed. I propose a fads model of Summers (1986) with time-varying variance.

Understanding statistical properties of nominal exchange rates is helpful in assessing the risk and return characteristics of foreign currency holding and pricing foreign currency options. Modification of conventional asset pricing models, such as the Black-Scholes option pricing model, may be made to incorporate empirical distributions of exchange rates. Furthermore, a statistical model that properly captures the statistical properties of exchange rates may provide a good foundation for a model used to forecast exchange rate movements. The model may be used for speculation or for exchange rate management policy.

The results in Chapter 3 show that percentage changes in spot rates are more peaked and fat-tailed than a normal distribution. Their distributions vary over time due to time-varying variance of the fundamental component. An AR(1)-GARCH(1,1) model is able to explain non-stationary variances of all currencies studied.

Having studied the statistical properties of and proposed a model to describe foreign exchange rates, I next examine whether there is a possibility of speculative profits' activities based on exchange rate movements. In an efficient market, prices should fully reflect information available to market participants. Weak-form efficiency suggests that it should be impossible for a speculator to consistently earn excess returns from a trading strategy based on past price movements.

Chapter 4 addresses the question: are foreign exchange markets efficient? If, in its simplest form, the Efficient Markets Hypothesis (EMH) holds, expected returns from holding a currency should be offset by the opportunity cost of holding funds. The expected changes in exchange rates should be matched by the interest rate differential under the joint hypothesis of market efficiency and no currency risk premium. Significant positive excess returns would imply market inefficiency. The hypothesis may be adjusted for risk. Under the joint hypothesis of market efficiency and risk premium, excess returns may be compensation for risk. Some excess returns from the trading strategy would be consistent with EMH.

If the foreign exchange markets are efficient in its weak form, any attempts to speculate based on historical price movements would be fruitless. But, if the markets are inefficient and exchange rate changes show some patterns, profitable opportunities will exist. From a viewpoint of policymakers, if the foreign exchange markets are efficient, government intervention may cause fluctuations and distort the level of exchange rates. If the fluctuations are large, exchange rates will be more volatile and may be destabilized. The excess volatility would impose costs on society who as a result makes less efficient allocative decisions (Froot and Thaler (1990)). However, if the markets are inefficient, government intervention may help stabilize exchange rates to ensure that the rates reflect fundamental values. Both producers and consumers would be benefit by such an action.

The results in this chapter show that relative strength trading strategies generate significant excess returns even after adjustment for the interest rate differential. The excess returns, however, vanish after they are adjusted for a constant currency risk premium.

Short-run excess returns represent a reward for risk. The results are thus consistent with the joint hypothesis of market efficiency and a constant risk premium.

The organizational plan for the dissertation is as follows. Chapter 2 is the study of time series behavior of monthly real exchange rates. Chapter 3 investigates the statistical properties of daily spot rates. Chapter 4 discusses market efficiency in the foreign exchange market. Chapter 5 provides a summary and economic implications of the results.

CHAPTER 2

TIME SERIES BEHAVIOR OF REAL EXCHANGE RATES

One of the most frequently tested elements of real exchange rate is the purchasing power parity (PPP) hypothesis. PPP states that the nominal exchange rate (X) is equal to the ratio of domestic prices (P) to foreign prices (P^*). Or, equivalently, the real exchange rate, $S = XP/P^*$, is always equal to one. PPP has been proposed as a theory characterizing long-run equilibrium in real exchange rates. If PPP holds, real exchange rates will, perhaps after temporary deviations, revert to long-run equilibrium. On the other hand, if real exchange rates follow a random walk, then PPP does not hold. Academia and policymakers believed that PPP would provide a useful approximation for movements in exchange rates when they began to float in 1973. However, as a result of high volatility exchange rates often deviate from the values implied by relative prices (e.g. Koedijk et al. (1998) and Lothian (1998)). Several studies attempt to empirically examine the behavior of foreign exchange rates. Earlier studies find a unit root in nominal and real exchange rates, concluding that exchange rates follow a random walk process (e.g., Meese and Singleton (1982) and Baillie and Bollerslev (1989)). Other studies, such as Frenkel (1981) and Meese and Rogoff (1983), compare structural models to a random walk model and conclude that exchange rates may be well-approximated by a random walk process. As a consequence, the representation of an exchange rate series as a random walk was common in the 1980s.

However, findings using recently developed techniques and an extended data set suggest that nominal and real exchange rates do not follow random walks.[1] These studies report that exchange rates contain a predictable component. For example, using long historical data set, Lothian (1998) finds that real exchange rates contain economically significant mean-reverting components. Frankel and Rose (1996), Jorion and Sweeney (1996), and Koedijk et al. (1998) pool data for different countries and find substantive evidence supporting PPP.[2]

The sticky-price monetary model of Dornbusch (1976) is another often used theory to explain mean reversion in exchange rates. The sticky-price model allows an exchange rate to overshoot its long-run equilibrium value and implies that exchange rates follow a mean reverting process. Short-run deviation is the result of the difference in the speed of adjustment between goods prices and asset prices. Therefore, if there is empirical evidence of mean reversion in exchange rates, an overshooting exchange rate model may be more appropriate than a flexible price model.

Edison et al. (1997) argue that unit root tests suffer from low power, suggesting that the contrasting results between recent and previous studies of real exchange rates may be the result of the characteristics of non-stationary series. A random walk process

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[1] These studies include Huizinga (1987), Abuaf and Jorion (1990), Liu and He (1991), Glen (1992), Frankel and Rose (1996), Jorion and Sweeney (1996), Lothian and Taylor (1996), Mark and Choi (1997), Koedijk et al. (1998), Lothian (1998), and Papell and Theodoridis (1998). Rogoff (1996) and Edison et al. (1997) provide reviews of studies of purchasing power parity.
[2] O'Connell (1997) questions the validity of the results of panel-data studies due to cross-sectional dependence. Later, Koedijk et al. (1998) introduce a methodology to deal with the cross-sectional dependency and provide strong support for PPP.

is a subset of the unit root null hypothesis and, as such, random walk implies a unit root, but not necessarily vice versa (see Cochrane (1988), and Lo and MacKinlay (1989)).[3]

In this study, I apply a variance ratio test originally employed in Lo and MacKinlay (1988) to test the random walk hypothesis in real exchange rates during the twenty-four years of the post-Bretton Woods period. If real exchange rates do not follow a pure random walk process, I examine what type of a process best describes the time-series behavior of real exchange rates. I find evidence suggesting that monthly real exchange rates during the post-Bretton Woods era do not follow a random walk. For example, approximately 11% of the variation in the monthly $/SF real exchange rate is predictable using the preceding month's exchange rate. Further analysis suggests that monthly real exchange rates may be represented by the sum of random walk and mean-reverting processes. The transitory component accounts for between 43% and 70% of the variation of monthly real exchange rates. This finding is consistent with the assumptions underlying the purchasing power parity hypothesis and Dornbusch's overshooting exchange rate model.

This chapter proceeds as follows. Section 1 explains the data and specification of the variance ratio test and Beveridge-Nelson decomposition. Section 2 discusses empirical results. Section 3 calibrates the significance of transitory components. Conclusion of the economic implications completes the chapter in section 4.

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[3] Beveridge and Nelson (1981) show that non-stationary series (a unit root) may be decomposed into permanent and transitory components. The permanent component follows a random walk and the transitory component is a stationary process with mean zero. Therefore, the conclusion of a unit root as evidence of a random walk is inappropriate.

Section 1:Data and Methodology

The study covers the period from January 1974 through December 1997 to avoid any effect resulting from the end of the Bretton Woods era in 1973. Data are obtained from the *International Financial Statistics* and include the natural logarithm of the exchange rates between the US dollar and i) the Canadian dollar (CD), ii) the French franc (FF), iii) the Japanese yen (JY), iv) the Deutschmark (DM), v) the British pound (BP), and vi) the Swiss franc (SF). The consumer price index (CPI) of each country is used to convert nominal exchange rates to real values.[4] The CPI series is employed since it is considered to be a more reasonable index of purchasing power (see Frenkel (1976) and Glen (1992)). Moreover, Glen shows that results using either the CPI or the wholesale price index (WPI) are only slightly different when testing for mean reversion.

Unit root tests provide one method used to test a random walk. As mentioned earlier, the unit root test can only identify whether an economic time series has a random walk component. Finding a unit root implies that a series is non-stationary, perhaps having both random walk and stationary components. Thus, the unit root test is not a direct test of the random walk hypothesis.[5] Moreover, in the exchange rate literature models are often tested for the adequacy of their fit with in-sample and out-of-sample data. For example, Frenkel (1981) and Meese and Rogoff (1983) compare the predictive performance of their empirical models with a naïve random model based on measures of prediction errors. Their empirical models fail to outperform the random

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[4] There are different views about the issue of which price index to use in the study of real exchange rates. In general, there are three price indices considered: CPI, wholesale price indices (WPI), and (less commonly used) GDP deflators. Bleaney and Mizen (1995) provide a thoughtful discussion about the advantages and disadvantages of each price index.

walk model, leading to the conclusion that exchange rates may be approximately represented by a random walk. Again, these studies provide only an indirect test of the random walk hypothesis.

Subsection 1.1: Variance Ratio Test

The variance ratio (VR) test of Lo and MacKinlay (1988) is a direct test of the random walk null hypothesis of uncorrelated increments. The VR test may be used to detect first-order autocorrelations of a series at various time horizons (q). The random walk hypothesis implies that the variance of random walk increments must be linear in the time interval. For example, the variance of the q-differences is q times the variance of the first differences. The VR test provides test statistics under both homoscedasticity, $Z1(q)$, and heteroscedasticity, $Z2(q)$, thus allowing for time-varying volatility. It also allows the use of overlapping data to analyze long-run serial correlation and permits long-run statistical inferences using a relatively small number of observations. In addition, Lo and MacKinlay (1989) and Faust (1992) show that the VR test is a powerful test of the random walk null hypothesis against several autoregressive moving-average (ARMA) alternatives.[6]

The variance ratio statistics may be calculated as

$$VR(q) = \frac{\sigma_c^2(q)}{\sigma_a^2(q)}, \tag{2.1}$$

[5] Edison et al. (1997) provide a discussion pertaining to the low power of unit root tests employed in previous studies.
[6] One popular alternative hypothesis against the random walk null is a fads model in which asset prices exhibit persistent but temporary deviations from fundamental values, as in Summers (1986) and Poterba and Summers (1988).

where $\sigma_a^2(q)$ and $\sigma_c^2(q)$ are unbiased estimators of the variances of the first difference and the q^{th} difference of overlapping q-period real exchange rate, S_t. The unbiased estimators $\sigma_a^2(q)$ and $\sigma_c^2(q)$ can be calculated as follows.

$$\sigma_a^2(q) = \frac{1}{nq-1}\sum_{t=1}^{nq} (S_t - S_{t-1} - \hat{\mu})^2, \tag{2.2}$$

where $\hat{\mu} = \frac{1}{nq}(S_{nq} - S_0)$, given $nq+1$ observations.

$$\sigma_c^2(q) = \frac{1}{m}\sum_{t=q}^{nq} (S_t - S_{t-q} - q\hat{\mu})^2, \tag{2.3}$$

where $m = \frac{q(nq-q+1)}{(1-q/nq)}$. The asymptotically standard normal test statistic under homoscedasticity is

$$Z1(q) = \frac{VR(q)-1}{\sqrt{\phi_1(q)}} \overset{a}{\sim} N(0,1), \tag{2.4}$$

where $\phi_1(q)$ is the asymptotic variance under homoscedasticity. The asymptotically standard normal test statistic under heteroscedasticity is

$$Z2(q) = \frac{VR(q)-1}{\sqrt{\phi_2(q)}} \overset{a}{\sim} N(0,1), \tag{2.5}$$

where $\phi_2(q)$ is the asymptotic variance under heteroscedasticity. Lo and MacKinlay (1988) demonstrate that both test statistics are asymptotically standard normal and thus statistical inference may be made using conventional critical values.

Huizinga (1987) and Glen (1992) apply the above logic to test the random walk hypothesis in monthly real exchange rates. The common conclusion drawn from these studies is rejection of the random walk hypothesis. Huizinga (1987) finds that during the

1974-1986 period, real exchange rates deviate from a random walk process by having a mean-reverting component. However, his spectral estimator of the variance ratio is not built upon well-developed asymptotic properties. Thus, statistical inference drawn from the study may be questionable. Using Lo and MacKinlay's VR test, Glen (1992) shows that rejection of the random walk hypothesis is due to positive serial correlations at medium lags. However, he does not find evidence of mean reversion for monthly real exchange rates and infers the evidence of long-run mean reversion from annual data. In section 4, I examine further the evidence of long-run mean reversion in monthly exchange rate data. In this study, I use one month as a base observation to calculate Z1(q) and Z2(q) statistics at various q-period horizons.

Subsection 1.2: Beveridge-Nelson Decomposition

Unlike previous studies applying a variance ratio test to the original series, this study further investigates the time series character of the transitory component. Beveridge and Nelson (1981) show that an integrated time series may be decomposed into a permanent and a transitory component and that the permanent component is always a random walk. Moreover, Quah (1992) shows that the permanent component is arbitrarily triviality so that the transitory component dominates the series at all finite horizons. Poterba and Summers (1988) suggest that the transitory component may characterize price movements that can not be explained by changing expectations about fundamentals. Thus, this paper also investigates the dynamic nature of the transitory component.

The assumption that changes in the non-stationary series are stationary with an ARMA representation underlies the Beveridge-Nelson decomposition. Beveridge and Nelson (1981) identify a permanent component, assumed to be a random walk with drift, as the long-run forecast profile of a series at any point in time. If the logarithm of real exchange rates (S_t) is a first-difference stationary process (W_t) of the ARMA (p,q) form, the permanent component may be described as

$$S_t^P = S_t + \lim_{k \to \infty}\left[\sum_{j=1}^{k} W_t(j) - k\mu\right], \qquad (2.6)$$

where μ is the rate of drift or the long-run mean.

The transitory component, which is a stationary process with mean zero, is then defined to be the difference between the permanent component and the realized value of a series. The innovations to both permanent and transitory components are perfectly correlated such that shocks to real exchange rates will have both permanent and temporary effects. Newbold (1990) provides the derivation and calculation of the permanent and transitory components. Let $Y_t(j) = W_t(j) - \mu$ be the difference of the ARMA(p,q) process W_t from the mean. The computation of the transitory component (S_t^T) may be implemented as follows.

$$S_t^T = \sum_{j=1}^{k} Y_t(j) + \left[\frac{1}{(1-\phi_1 - \dots - \phi_p)}\right]\sum_{j=1}^{p}\sum_{i=j}^{p} \phi_i Y_t(q-j+1), \qquad (2.7)$$

where $Y_t(i) = Y_{t+i}, i \le 0$. The permanent component may be obtained by substituting equation (2.7) into equation (2.6). I use this decomposition algorithm in the following section.

Section 2: Empirical Results

Table 2.1 presents preliminary summary statistics, including the mean, standard deviation, autocorrelation coefficients, $\rho(i)$, and Box-Pierce Q-statistics for changes in monthly real exchange rates. The standard errors are $1/\sqrt{T}$ under the random walk null hypothesis of independently and identically distributed (IID) increments. With a sample size of 288 observations, the standard error is 0.059. First-differences of monthly real exchange rates (Table 2.1) have first-order autocorrelations ranging from 0.144 to 0.337. All exchange rate series exhibit positive first-order serial correlations statistically significant at the 5 percent level. In terms of regression analysis, the square of the first-order autocorrelation is simply the R^2 of a regression of a variable on a constant and its first lag. Thus, in the case of the $/JY real exchange rate, a first-order autocorrelation of 0.337 implies that 11.36% of the variation in the monthly real $/Yen exchange rate may be predicted by the preceding month's rate.

In addition, the Box-Pierce Q-statistics suggest rejection of the random walk null hypothesis of IID for each of the currencies included in this study, with the exception of the $/CD exchange rate.[7] The serial correlation in the exchange rate series causes rejection of the IID null hypothesis in Table 2.1. However, several studies show that exchange rates possess time-varying volatilities. The analysis so far has not shown whether rejection of IID is robust to the presence of heteroscedasticity. This concern is discussed next.

[7] Note that the Q-statistic is the sum of the square of the autocorrelations. As evident in Table 2.1, the first six autocorrelations of the $/CD exchange rate are relatively small.

Table 2.1

Means, Standard Deviations, Autocorrelation Coefficients, and Box-Pierce Q Statistics

	CD	FF	JY	DM	BP	SF
Mean(x100)	-0.105	-0.020	0.129	-0.031	0.097	0.091
SD(x100)	1.104	2.636	2.917	2.720	2.762	3.082
ρ1	0.144*	0.265*	0.337*	0.300*	0.342*	0.329*
ρ2	-0.002	0.029	0.023	0.048	-0.010	0.039
ρ3	0.008	0.117*	0.055	0.033	0.034	0.038
ρ4	-0.000	0.018	0.056	-0.030	-0.011	-0.034
ρ5	0.017	0.020	0.002	-0.033	-0.055	-0.033
ρ6	0.026	-0.003	-0.068	-0.000	-0.017	0.029
ρ7	0.032	-0.012	-0.019	0.013	-0.022	-0.012
ρ8	0.178*	0.053	0.057	0.063	0.014	0.047
ρ9	0.065	0.047	0.041	0.076	0.033	0.046
ρ10	0.197*	0.059	0.020	0.109	-0.021	0.063
ρ11	0.114	-0.004	0.117*	0.040	0.051	0.001
ρ12	-0.084	0.001	0.115	0.032	0.103	0.012
Q(4)	6.08	24.86*	35.09*	27.51*	34.36*	32.71*
Q(6)	6.38	24.98*	36.45*	27.84*	35.32*	33.28*
Q(12)	35.15*	27.57*	46.30*	35.19*	40.00*	35.84*

(*) denotes statistically significant at the 5 percent level.

Table 2.2 reports, for each currency, the estimated variance ratios VR(q) in the first rows followed by the estimated homoscedastic Z1(q) statistics in the second rows and the estimated heteroscedasticity-consistent Z2(q) statistics in the third rows. The significance of Z1(q) statistics suggests the rejection of the random walk null hypothesis under the assumption of homoscedasticity (IID increments). The significance of Z2(q) statistics implies the rejection of the null that is robust to heteroscedasticity. Lo and MacKinlay (1989) show that the empirical size of the VR test is reasonably close to its nominal value for sample sizes greater than thirty-two. However, when q is large relative to the sample size, the VR test may have little power. Following Lo and MacKinlay (1989), I choose q to be no more than one-half the number of observations, so that $q < 144$ in this study. The discussion of the results will be based on the Z2(q) statistics to provide proper statistical inference, since there is substantial evidence of time-varying volatilities in exchange rates (Bollerslev, Chou, and Kroner (1992)). In general, the results show that the random walk hypothesis is rejected at the 5 percent level for each of the currencies studied and the results are robust in the presence of heteroscedasticity. The estimates of variance ratios are larger than one, first increasing, then decreasing with time horizons. The variance ratios greater than one are expected since the variance ratio is approximately equal to 1.0 plus the first-order autocorrelation coefficients, ρ(q), of the first-differences of real exchange rates for q-period horizons (see Lo and MacKinlay (1988)).

$$\frac{VR(2q)}{VR(q)} = 1 + \rho(q) \tag{2.8}$$

For example, with the value of q equal to 2, the variance ratio of the $/FF real exchange rate is 1.27. It implies that the first-order autocorrelation for changes in $/FF exchange rates is approximately 0.27, which is consistent with the value reported in Table 2.1. Increasing variance ratios imply positive serial correlation in multiperiod changes in exchange rates. For example, for a six-month horizon of the $/DM real exchange rate, VR(12) / VR(6) = 1.105. This implies that the first-order autocorrelation coefficient of a six-month change in the $/DM rate is about 10.5%.[8]

One explanation of the rejection of the random walk hypothesis is that the series may be described by the sum of a random walk and a mean reverting component (see Fama and French (1988), and Poterba and Summers (1988)). For a process described by the sum of a random walk and a stationary process, the variance ratio should converge to a number less than unity as q increases, as shown by the evidence in Table 2.2. Mean reversion requires negative serial correlation in changes in the exchange rates. However, the evidence from Tables 2.1 and 2.2 shows positive first-order autocorrelations at lower lags. Although the VR statistics for each currency are below unity after a certain time horizon, they are not statistically significant different from one.[9] For instance, the VR statistic of the $/JY real exchange rate is equal to 0.98 at a sixty-month horizon and decreases thereafter. This evidence would immediately imply mean reversion of real exchange rates if the VR statistic were significant.

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[8] The results of six-year subperiods exhibit similar patterns observed in Table 2.2. I focus on the full sample period to maintain a fair number of observations to obtain reliable statistical inference of $Z1(q)$ and $Z2(q)$ statistics which depend on asymptotic distribution properties.

[9] Insignificant VR statistics may be a result of rising standard errors as horizons increase. Summer (1986) discusses why statistical tests may have low power.

Table 2.2

Estimates of Variance Ratios and Z-Statistics for Monthly Real Exchange Rate Series

q =	2	4	6	12	18	24	30	36	42
CD	1.13	1.19	1.20	1.52	1.75	1.97	2.11	2.15	2.13
Z1(q)	2.22*	1.67	1.35	2.35*	2.69*	3.01*	3.06*	2.86*	2.60*
Z2(q)	2.07*	2.08*	1.89	3.62*	4.23*	4.77*	4.94*	4.63*	4.21*
FF	1.27	1.51	1.64	1.85	1.94	1.90	1.85	1.82	1.72
Z1(q)	4.54*	4.57*	4.40*	3.85*	3.38*	2.77*	2.34*	2.04*	1.67
Z2(q)	4.48*	6.13*	6.14*	5.70*	5.11*	4.26*	3.63*	3.18*	2.60*
JY	1.33	1.53	1.65	1.78	1.89	1.79	1.72	1.64	1.56
Z1(q)	5.57*	4.80*	4.42*	3.50*	3.21*	2.45*	1.97*	1.60	1.28
Z2(q)	4.97*	6.52*	6.44*	5.01*	4.84*	3.83*	3.14*	2.54*	2.04*
DM	1.30	1.52	1.57	1.74	1.90	1.86	1.80	1.71	1.63
Z1(q)	5.10*	4.73*	3.92*	3.33*	3.26*	2.67*	2.19*	1.78	1.45
Z2(q)	5.03*	6.31*	5.63*	5.09*	5.04*	4.18*	3.47*	2.82*	2.31*
BP	1.34	1.51	1.55	1.56	1.50	1.53	1.56	1.54	1.49
Z1(q)	5.68*	4.59*	3.74*	2.52*	1.81	1.62	1.54	1.35	1.12
Z2(q)	4.41*	5.25*	4.45*	3.36*	2.55*	2.39*	2.35*	2.11*	1.76
SF	1.33	1.55	1.60	1.73	1.75	1.64	1.48	1.31	1.16
Z1(q)	5.53*	5.00*	4.13*	3.28*	2.70*	1.98*	1.33	0.78	0.37
Z2(q)	5.75*	6.71*	5.82*	5.05*	4.19*	3.12*	2.14*	1.26	0.59

(*) denotes statistically significant at the 5 percent level.

Table 2.2 (Continued)

q =	48	60	72	84	108	120	132	144
CD	2.10	1.89	1.60	1.25	0.95	0.87	0.76	0.58
Z1(q)	2.37*	1.71	1.05	0.40	-0.07	-0.17	-0.31	-0.51
Z2(q)	3.85*	2.80*	1.74	0.66	-0.11	-0.30	-0.53	-0.89
FF	1.64	1.49	1.25	0.98	0.66	0.57	0.41	0.25
Z1(q)	1.38	0.93	0.44	-0.04	-0.48	-0.59	-0.76	-0.92
Z2(q)	2.18*	1.48	0.70	-0.06	-0.77	-0.95	-1.25	-1.52
JY	1.42	0.98	0.74	0.54	0.42	0.40	0.38	0.32
Z1(q)	0.91	-0.04	-0.45	-0.74	-0.83	-0.80	-0.79	-0.84
Z2(q)	1.47	-0.06	-0.74	-1.23	-1.38	-1.35	-1.34	-1.43
DM	1.57	1.50	1.32	1.08	0.75	0.70	0.56	0.36
Z1(q)	1.22	0.95	0.55	0.14	-0.35	-0.40	-0.56	-0.79
Z2(q)	1.97*	1.55	0.91	0.22	-0.58	-0.67	-0.93	-1.32
BP	1.43	1.14	0.86	0.56	0.26	0.19	0.14	0.13
Z1(q)	0.93	0.27	-0.24	-0.72	-1.05	-1.09	-1.10	-1.08
Z2(q)	1.45	0.43	-0.39	-1.15	-1.69	-1.77	-1.80	-1.76
SF	1.07	1.01	0.90	0.65	0.40	0.40	0.30	0.16
Z1(q)	0.15	0.01	-0.18	-0.56	-0.85	-0.81	-0.90	-1.03
Z2(q)	0.24	0.02	-0.30	-0.92	-1.40	-1.35	-1.52	-1.74

(*) denotes statistically significant at the 5 percent level.

The evidence merely suggests that monthly real exchange rates neither follow a random walk nor fit a mean reverting process. Is mean aversion (an explosive process) an alternative explanation of the behavior of monthly real exchange rates? If yes, why do we observe an appreciation and then a depreciation of the dollar over time? I examine these questions below.

Beveridge and Nelson (1981) show that non-stationary series may be decomposed into permanent and transitory components. Before the implementation of the decomposition, an autoregressive moving average (ARMA) representation for the first-differences of exchange rates must be identified. Table 2.3 shows the ARMA models for changes in monthly real exchange rates during the sample period. For example, the ARMA representation of the $/BP exchange rate is an ARMA(3,5) process. The selection of AR's and MA's lags is based on the Akaike information criteria (AIC) and the absence of serial correlation in residuals using Q-statistics. The Box-Jenkins procedure is used to estimate the ARMA process.

Table 2.3

The Selection of ARMA Models for Changes in Monthly Real Exchange Rates

	AR	MA	AIC	Q-Statistics	P-values
CD	2	11	-973.86	32.07	0.10
FF	1	3	-487.60	22.27	0.90
JY	3	3	-443.68	31.94	0.37
DM	2	3	-475.84	24.80	0.78
BP	3	5	-486.92	29.00	0.41
SF	2	4	-409.30	25.54	0.70

Table 2.4 presents the variance ratios, and $Z2(q)$ statistics for the permanent components (panel A) and the transitory components (panel B). The horizons are truncated to only forty-eight months because the VR statistics are, in general, not statistically significant thereafter. Furthermore, Lo and MacKinlay suggest using the values of q that are less than one-eighth of the sample size (corresponding to thirty-six

months in this study) to achieve more accurate statistical inference using the asymptotic distribution (Glen (1992)). The following discussion is also confined to only the Z2(q) statistics. Since by construction the permanent component must follow a random walk process, the variance ratios should not be significantly different from one for all time horizons. Even though the results from Table 2.4 panel A generally confirm that the permanent components follow a random walk, the Z2(q) statistics for some q periods suggest the opposite. For example, the VR(2) of 0.65 of the $/SF exchange rate and the significant Z2(q) statistic of -3.20 imply a negative first-order autocorrelation in the $/SF permanent component. These rejections, however, appear to be occasional and may be attributed to Type I errors.[10]

The variance ratio tests in Table 2.4 panel B comply with the definition of the transitory component. There are mean reverting components in all currencies. For example, the first-order autocorrelation of the $/SF series is a negative 0.63. Also as q increases, the variance ratios converge to zero, which is consistent with the statistical characteristics of a stationary process. Mean reversion also suggests that part of a shock to real exchange rates is temporary, implying that exchange rates will revert back to their long-run equilibrium rate.

[10] This negative first-order autocorrelation may be the result of the pre-specified ARMA model. The ARMA(2,4) was selected for the $/SF series based on the minimum AIC value and whiten the residuals when the maximum lags are initially constrained to ARMA(3,5). The specified ARMA process in the Beveridge-Nelson decomposition is subjective. The selection is determined by the analysis of the data and it varies under different conditions. For example, if the maximum lags are allowed up to ARMA(6,5), the first-difference of the $/SF series may also be specified as the ARMA(5,5) model.

Table 2.4

Estimates of Variance Ratios and Z-Statistics for the Permanent and Transitory Components

Panel A: Permanent Components

Q=	2	4	6	12	24	36	48
CD	0.79	0.72	0.66	0.75	0.87	0.96	0.92
Z2(q)	-1.69	-1.93	-2.02*	-1.19	-0.44	-0.10	-0.20
FF	1.13	1.26	1.36	1.58	1.56	1.49	1.33
Z2(q)	1.23	1.50	1.78	2.34*	2.01*	1.61	1.03
JY	0.72	0.58	0.56	0.56	0.57	0.52	0.46
Z2(q)	-1.29	-1.85	-1.85	-1.75	-1.57	-1.64	-1.77
DM	0.92	0.96	0.90	0.94	1.01	0.94	0.87
Z2(q)	-0.79	-0.36	-0.69	-0.30	0.03	-0.20	-0.39
BP	1.05	1.02	0.86	0.63	0.60	0.58	0.50
Z2(q)	0.75	0.17	-1.24	-2.20*	-1.79	-1.61	-1.62
SF	0.65	0.71	0.74	0.76	0.71	0.57	0.47
Z2(q)	-3.20*	-2.00*	-1.51	-1.09	-1.08	-1.42	-1.58

(*) denotes statistically significant at the 5 percent level.

Panel B: Transitory Components

Q=	2	4	6	12	24	36	48
CD	0.72	0.62	0.47	0.25	0.10	0.09	0.05
Z2(q)	-1.98*	-2.31*	-2.88*	-3.19*	-2.59*	-2.19*	-2.02*
FF	0.86	0.48	0.30	0.18	0.13	0.10	0.07
Z2(q)	-0.96	-2.29*	-2.59*	-2.61*	-2.63*	-2.51*	-2.48*
JY	0.52	0.27	0.21	0.09	0.04	0.03	0.02
Z2(q)	-2.02*	-2.94*	-3.14*	-3.43*	-3.35*	-3.21*	-3.08*
DM	0.61	0.41	0.16	0.10	0.05	0.04	0.04
Z2(q)	-2.68*	-3.73*	-4.09*	-3.29*	-2.80*	-2.59*	-2.28*
BP	0.82	0.64	0.45	0.14	0.08	0.06	0.05
Z2(q)	-2.10*	-3.08*	-4.28*	-4.64*	-3.61*	-3.28*	-2.93*
SF	0.37	0.24	0.15	0.08	0.04	0.03	0.02
Z2(q)	-4.96*	-4.62*	-4.39*	-3.85*	-3.22*	-2.96*	-2.75*

(*) denotes statistically significant at the 5 percent level.

Subsection 2.1: Interim Summary

The results indicate that real exchange rates during the 1974-1997 period do not follow a pure random walk process. The analysis of autocorrelations and variance ratio (VR) tests suggests that changes in monthly real exchange rates exhibit positive first-order autocorrelations at lower lags up to, in general, four-year horizons.

The positive serial correlations at lower lags suggest that real exchange rates may never revert back to their (long-run) equilibrium values. The VR statistics for longer horizons indicate negative, but not statistically significant, autocorrelations. Thus, these results fail to support the hypothesis of long-run mean reversion in monthly exchange rates.[11]

Using the Beveridge-Nelson decomposition technique, each of the real exchange rates may be decomposed into a permanent and a transitory component. The permanent component follows a random walk process. The transitory component exhibits negative first-order autocorrelation and is stationary with mean zero. Therefore, real exchange rates may be well represented by the sum of random walk and mean-reverting processes.

Section 3: The Importance of Transitory Components[12]

Exchange rate models implied by, i.e., PPP and the interest rate parity, suggest that changes in exchange rates should respond only to changes in fundamentals, such as relative prices, interest rate differentials, and trade balance. The permanent component

[11] The positive serial correlations at medium lags also lead Glen (1992) to conclude evidence of no mean reversion in monthly real exchange rates.

[12] An alternative approach to analyze the relative importance of a transitory component is to calibrate models explaining the data, as I already did in the empirical result section. However, the ARMA specifications in Table 2.3 are subjective and the rejection of the random walk null hypothesis of the permanent components (Table 2.4 panel A) appears occasionally due to perhaps Type I errors. As a result,

represents the value of an exchange rate on its long-run equilibrium path. Deviations from its long-run value, i.e., the overshooting phenomenon in the sticky-price model of Dornbusch (1976), fads, or bubbles, are expected to appear in the transitory component.

Poterba and Summers (1988) show that the variance ratios estimates can be used to measure the importance of the transitory component. I define the logarithm of real exchange rates (S_t) as the sum of a permanent (S_t^P) and a transitory (S_t^T) component. The permanent component is assumed to follow a random walk process and the transitory component is a stationary AR(1) process.[13] I have the following models.

$$\begin{aligned} S_t &= S_t^P + S_t^T \\ S_t^P - S_{t-1}^P &= \varepsilon_t \\ S_t^T &= \rho_1 S_{t-1}^T + v_t, \end{aligned} \tag{2.9}$$

where ε_t and v_t are innovations in the nonstationary and stationary components, respectively. The first-order autocorrelation coefficient (ρ_l) is a measure of the persistence of the transitory component. If ε_t and v_t are independent, ΔS_t follows an ARMA(1,1) process of the form

$$\Delta S_t = \varepsilon_t + (1-L)(1-\rho_1 L)^{-1} v_t, \tag{2.10}$$

where L is the lag operator. To gauge the significance of the transitory component relative to the permanent component, I must assume that ε_t and v_t are orthogonal. The share of return variation due to transitory factors is determined by the relative size of

I follow the Poterba and Summers approach which does not require the specifications of the data and thus the transitory components.

[13] This is a fads model proposed in Summers (1986) and Poterba and Summers (1988).

σ_ε^2 and σ_v^2.[14] I use estimated VR statistics from the original series (Table 2.2) to measure the importance of the transitory components.

Given the above assumptions, the variance of q-period changes in real exchange rates is

$$\sigma^2(q) = q\sigma_\varepsilon^2 + 2(1-\rho(q))\sigma_T^2, \tag{2.11}$$

where σ_ε^2 is the variance of innovations to the permanent component and σ_T^2 and $\rho(q)$ are the variance and q-period autocorrelation of the transitory component. If σ_ε^2 = 1, the variance of one-period changes in exchange rates is $\sigma_a^2 = 1 + 2(1-\rho_1)\sigma_T^2$. From equation (2.9), I know that $\sigma_T^2 = \sigma_v^2(1-\rho_1)^{-2}$. Therefore, the share of the variance of changes in exchange rates attributable to the stationary component is $2\sigma_v^2/(1+\rho_1+2\sigma_v^2)$.

Poterba and Summers derive closed-form formulae to calculate σ_ε^2 and σ_T^2 over two horizons q and q' as

$$\sigma_\varepsilon^2 = \frac{\sigma_a^2[VR(q)(1-\rho(q'))q - VR(q')(1-\rho(q))q']}{(1-\rho(q'))q-(1-\rho(q))q'}, \tag{2.12}$$

$$\sigma_T^2 = \frac{\sigma_a^2 q'[VR(q)-VR(q')]q}{2[(1-\rho(q))q'-(1-\rho(q'))q]}, \tag{2.13}$$

where σ_a^2 is the variance of one-period changes in exchange rates.

I calculate the standard deviation of the transitory component (σ_T) and the proportion of monthly variation due to transitory component, $\delta = 1-\sigma_\varepsilon^2/\sigma_a^2$, based on

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[14] If ε_t and v_t are perfectly correlated, σ_ε^2 is equal to σ_T^2 and as such the relative importance can not be illustrated.

several values of $\rho(q)$ and $\rho(q')$. To assume the values of $\rho(q)$ and $\rho(q')$, I analyze the results in Table 4(b). Regardless of the ARMA specifications of the currencies, the transitory components die out at about 4 years, implying a half-life of 2 years. Given an AR(1) process $Y_t = \alpha + \beta Y_{t-1} + \eta_t$, a half-life can be calculated as $\ln(1/2)/\ln(\beta)$. Thus, with a half-life of 24 months, the first order autocorrelation (ρ_1) is 0.97. With geometric decay as $\rho_j = \beta^j$, one-year (ρ_{12}) and seven-year (ρ_{84}) autocorrelations of the transitory components are approximately 0.70 and 0.08, respectively.[15]

Table 2.5 reports estimates of σ_T and δ based on different values of ρ_{12} and ρ_{84}. I analyze the results by first postulating that $\rho_{84} = 0$. In general, increasing the assumed persistence of the transitory component (movement from $\rho_{12} = 0.00$ to $\rho_{12} = 0.70$) raises both its standard deviation and its contribution to the variance of changes in real exchange rates, suggesting increased importance of the transitory component. The transitory components have standard deviations ranging from 1.5% to 20% depending on the assumed values of ρ_{12}. The portions of the variation of changes in monthly real exchange rates due to the transitory components are shown in the columns labeled δ of Table 2.5.

I first discuss the two extreme cases. For the $/CD real exchange rate, the variation in monthly exchange rates is entirely dominated by the permanent component (indicated by the '-' signs). For several cases in which movement in the transitory components is highly persistent (ρ_{12} = 0.70), the transitory components dominate the movement in monthly real exchange rates (indicated by the '+' signs).

[15] The horizons of 12 and 84 months are arbitrarily chosen to be certain that the horizons are long enough

Table 2.5

The Relative Importance of Permanent and Transitory Components of Real Exchange Rates

	$\rho_{12} = 0.00$		$\rho_{12} = 0.35$		$\rho_{12} = 0.70$	
	σ_T	δ	σ_T	δ	σ_T	δ
CD						
$\rho_{84} = 0.00$	1.53%	-	1.98%	-	3.56%	-
$\rho_{84} = 0.08$	1.52%	-	1.96%	-	3.44%	-
$\rho_{84} = 0.15$	1.51%	-	1.94%	-	3.34%	-
FF						
$\rho_{84} = 0.00$	6.43%	0.169	8.36%	0.269	15.02%	0.818
$\rho_{84} = 0.08$	6.39%	0.155	8.27%	0.245	14.50%	0.705
$\rho_{84} = 0.15$	6.35%	0.144	8.19%	0.224	14.09%	0.618
JY						
$\rho_{84} = 0.00$	8.57%	0.665	11.14%	0.807	20.01%	+
$\rho_{84} = 0.08$	8.51%	0.646	11.02%	0.772	19.32%	+
$\rho_{84} = 0.15$	8.46%	0.630	10.91%	0.742	18.77%	+
DM						
$\rho_{84} = 0.00$	5.78%	0.025	7.52%	0.100	13.50%	0.511
$\rho_{84} = 0.08$	5.74%	0.015	7.43%	0.082	13.04%	0.426
$\rho_{84} = 0.15$	5.71%	0.006	7.36%	0.066	12.67%	0.361
BP						
$\rho_{84} = 0.00$	7.31%	0.612	9.51%	0.727	17.08%	+
$\rho_{84} = 0.08$	7.26%	0.597	9.40%	0.699	16.49%	+
$\rho_{84} = 0.15$	7.22%	0.583	9.31%	0.675	16.02%	+
SF						
$\rho_{84} = 0.00$	8.41%	0.525	10.94%	0.648	19.65%	+
$\rho_{84} = 0.08$	8.36%	0.508	10.82%	0.617	18.97%	+
$\rho_{84} = 0.15$	8.31%	0.494	10.71%	0.592	18.43%	+

to see the variation of the transitory components.

The data show that there are long swing exchange rates that do not appear to be driven by changes in the fundamental factors. In most cases, the transitory components account for between 50% and 80% of the monthly variance.

As mentioned earlier, the most relevant ρ_{12} and ρ_{84} values in this study are probably 0.70 and 0.08, respectively. Besides the two extreme cases (the '-' sign for $/CD exchange rate and the '+' signs for $/JY, $/BP, and $/SF exchange rates), the transitory components account for between 43% and 70% of the monthly variance of changes in real exchange rates and have standard deviations about 14%. Therefore, the analysis in this section confirms the evidence presented above suggesting that there are transitory components in monthly real exchange rates.

Section 4: Conclusion

Understanding the underlying process determining foreign exchange rates should help in creating models that provide satisfactory empirical performance. The results for the 1974-1997 period show positive first-order autocorrelations at short horizons and negative, though not statistically significant, serial correlations at long horizons. Further analysis suggests that monthly real exchange rates may be well approximated by the sum of random walk and mean-reverting processes. The presence of a transitory component in the real exchange rate data is highly persistent and may be responsible for long swings of real exchange rates from a long-run equilibrium path. Therefore, empirical exchange rate modeling should properly incorporate this time-series characteristic.[16]

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[16] Engel and Hamilton (1990) propose the long swings hypothesis to explain movements of the U.S. dollar. They also call for a development of a model that allows persistence in exchange rate movements.

In addition to improving modeling, understanding the time-series behavior of real exchange rates is also important for the following reasons. First, from the investor's perspective, it helps assess the risk and expected returns of holding foreign currencies. Second, from the firm's point of view, it helps determine the degree of currency risk exposure associated with firms' foreign operations. Finally, from the policymaker's viewpoint, it may help formulate an exchange rate management policy and a corresponding domestic monetary policy.

Permanent and transitory components of real exchange rates convey different types of information and could be utilized for different purposes. The permanent component represents the long-run equilibrium value or trend behavior of real exchange rates. Policymakers who are concerned with the stability and level of exchange rates are expected to be primarily interested in the permanent component of exchange rates. The transitory component exhibits mean reversion and represents a deviation of an exchange rate from its fundamental value. Speculators may pay close attention to the transitory element in exchange rates. Moreover, since the transitory component appears to be cyclical, firms, by focusing on this element, may be able to avoid the negative impact of transitory changes in exchange rates by adopting appropriate hedging strategies.

CHAPTER 3

STATISTICAL PROPERTIES OF

DAILY SPOT RATES

Economists have long attempted to identify the underlying distributions of financial asset prices. It is widely acknowledged that the distributions of exchange rates at high frequency have fatter tails than the normal distribution. Some studies offer alternative distributions such as the stable Paretian distribution, the Student *t*-distribution, and a mixture of two normal distribution (e.g., Rogalski and Vinso (1978), Calderon-Rossell and Ben-Horim (1982), and Boothe and Glassman (1987)). Several studies extend the autoregressive conditional heteroscedastic (ARCH) model of Engle (1982) and the generalized ARCH (GARCH) of Bollerslev (1986) to explain the behavior of exchange rates and reach a conclusion that their distributions vary over time (e.g., Bollerslev (1987), Hsieh (1988), and see Bollerslev, Chou and Kroner (1992) for a survey of ARCH modeling in finance).

Although no conclusive agreement about the distribution that best characterizes exchange rates has been reached, it is generally agreed that time-varying mean and variance might be responsible for the esoteric behavior of exchange rates. Is non-normality the result of market inefficiency, a bad model, or the animal spirits of Keynes? The search for the proper statistical distribution of the exchange rates continues. This study offers an alternative way to examine the distribution of exchange rates. I propose to separate the exchange rate series into fundamental (permanent) and non-fundamental (transitory) components. Beveridge and Nelson (1981) show that non-stationary series can be decomposed into permanent and transitory components. The permanent component is always a random walk with drift and the transitory component is a stationary process with mean zero. Since exchange rate series are commonly known to be non-stationary, they may be decomposed as well.

Understanding the underlying process determining foreign exchange rates is important especially in the area of assessing the expected returns (mean) and riskiness (variance) of international asset holding and pricing foreign currency options. Conventional asset pricing models assume that asset prices are unpredictable and thus follow a martingale process. However, when an asset price (mean) is correlated to its own past values (serial correlation), the standard asset pricing models are not applicable. For example, if asset prices are predictable in the mean, the standard Black-Scholes option pricing model must be modified to incorporate serial correlation, as illustrated in Lo and Wang (1995).[17]

Furthermore, the form of the distribution and its parameters are used to model and forecast the movement of exchange rates. By assuming an inappropriate underlying distribution, the postulated model will provide inaccurate prediction. For example, the conventional exchange rates models usually assume exchange rates are normally distributed and, thus, can be explained by two parameters -- mean and variance. However, if the rates follow other forms of distribution, such as the stable Paretian or

Student *t*-distribution, the estimated parameters from the traditional regression analysis can provide misleading results.

The purpose of this study is to examine the statistical distribution of exchange rates when they are too volatile to be accounted for by subsequent changes in fundamentals. This study will investigate the statistical distributions of both permanent and transitory components. Current speculative prices like exchange rates should incorporate all relevant information about the underlying fundamentals and only change in response to the advent of new information. From a theoretical view, changes in exchange rates should respond only to changes in the underlying fundamentals, such as relative prices, interest rate differentials, trade balances, and so forth. Analogously, the permanent component that is the value of exchange rates as if it were on the long-run equilibrium path, should represent such changes. In other words, changes in exchange rates should respond only to current innovation such that all prices movements are permanent.[18] However, when the exchange rate temporarily deviates from its long-run value, such as the overshooting phenomenon in the sticky-price model of Dornbusch (1976), the departure should reside in the transitory component.[19] This study examines statistical properties of both components and provides discussion pertaining to the Efficient Market Hypothesis. Furthermore, I offer a statistical model to capture the statistical properties of daily spot rates.

[17]Also, if the volatility of the underlying assets is time-varying and, say, follows a GARCH process, options can be priced as shown in, e.g., Duan (1995) and Ritchken and Trevor (1999).

[18]This implies that exchange rates follow a random walk. Following Beveridge and Nelson (1981), the random walk process can be represented by the permanent component.

[19]Previous studies, such as Huizinga (1987) and Mark and Choi (1997), have decomposed the log of real exchange rates into the fundamental or long-run equilibrium value, corresponding to the permanent component, and a covariance stationary term, corresponding to the transitory component. They also consider a transitory part to be the deviation of the real exchange rate from its fundamental value.

The analysis shows that distributions of changes in spot rates vary over time due to changes in variance of the fundamental component. The appraisal of the non-fundamental component implies the presence of deviation of an exchange rate from its long-run equilibrium value. The results can be reconciled with two market efficiency views that (1) exchange rates may be drawn from a normal distribution with time-varying variance and (2) exchange rates may contain discrete jumps possibly due to market overreaction or government intervention. In addition, I model the logarithm of daily spot rates as the sum of a permanent and a transitory component. The permanent component follows a random walk with dependent but uncorrelated increments. The transitory component is a mean-stationary AR(1) process with time-varying variance. This proposed model is based on a fads model of Summers (1986) with non-stationary variance. The GARCH(1,1) errors capture time-varying variances for all currencies studied here. The AR(1)-GARCH(1,1) model provides satisfactory empirical performance with the exception of the French franc and the Japanese yen.

This chapter proceeds as follows. Section 1 describes the data and specification of the Beveridge-Nelson decomposition. Section 2 illustrates statistical properties of daily spot rate changes, permanent components, and transitory components. Section 3 examines non-stationarity hypothesis of mean and variance. Section 4 discusses two market efficiency views. I propose a fads model to explain the data in section 5. Conclusion completes the paper in section 6.

Section 1: Data and Methodology

Data are obtained from the Policy Analysis Computing & Information Facility in Commerce (PACIFIC) Exchange Rate Service. Investigated currencies are daily exchange rates between the U.S. dollar and i) the German mark (DM), ii) the British pound (BP), iii) the French franc (FF), iv) the Japanese yen (JY), v) the Swiss franc (SF), and vi) the Canadian dollar(CD) for the period from January 2, 1974 to August 31, 1998 (a total of 6433 observations).

Daily spot rates (S_t) are converted to percentage changes in continuously compounded rates (R_t) as $R_t = 100 * \ln(S_t / S_{t-1})$. Natural logs are used to make the analysis independent of the choice of home currency -- that is, independent whether exchange rates are expressed as direct or indirect quotes (Fama(1984)). The use of logs is also consistent with a statistical model proposed in section 6. A special adjustment for returns is made to accommodate holidays. Missing prices are replaced by previous day prices so that during holidays returns from holding currencies are zero. Returns on the next trading days are calculated as usual. Weekend prices (and returns) are reported as missing, however.

Beveridge and Nelson (1981) introduce an approach to decompose an autoregressive integrated moving average (ARIMA) time series into a permanent and a transitory component. They assume the economic times series, S_t, is non-stationary; but, its first differences, $R_t = S_t - S_{t-1}$, are covariance stationary and can be represented by the ARMA process. Using the Wold decomposition theorem, R_t can be expressed as

$$R_t = \mu + \varepsilon_t + \psi_1 \varepsilon_t + \ldots, \quad (3.1)$$

where *m* is the long-run mean and $\varepsilon_t \sim (0,s^2)$ are uncorrelated error terms. Parameters are assumed constant. If R_t follows an ARMA(p, q) process, it can also be described as

$$R_t = \mu + \phi_1 R_{t-1} + \ldots + \phi_p R_{t-p} + \varepsilon_t + \theta_1 \varepsilon_{t-1} + \ldots + \theta_q \varepsilon_{t-q}, \tag{3.2}$$

where ϕ and θ are autoregressive and moving average parameters, respectively. Equation (3.2) is stable and regicide for the mean provided that the roots of $1 - \phi_1 Z - \phi_2 Z^2 - \ldots - \phi_p Z^p = 0$ lie outside the unit circle. The forecast profile k-periods ahead and conditional on past information through time t is $\hat{S}_t(k)$ and it is described by

$$\begin{aligned} \hat{S}_t(k) &= E\left[S_{t+k} \mid S_t, S_{t-1}, \ldots\right] \\ \hat{S}_t(k) &= S_t + E\left[R_{t+1} + \ldots + R_{t+k} \mid R_t, R_{t-1}, \ldots\right] \\ \hat{S}_t(k) &= S_t + \sum_{j=1}^{k} \hat{R}_t(j). \end{aligned} \tag{3.3}$$

Since R_t is stationary for long run forecast horizons, $\hat{S}_t(k)$ is asymptotic to a linear function of forecast horizon k with slope m. Beveridge and Nelson interpret this forecast profile as *a permanent or trend component* and it is expressed as follows.

$$\begin{aligned} S_t^P &= S_t + \left(\sum_{i=1}^{\infty} \psi_i\right)\varepsilon_t + \left(\sum_{i=2}^{\infty} \psi_i\right)\varepsilon_{t-1} + \ldots \\ S_t^P &= S_t + \lim_{k\to\infty}\left[\sum_{j=1}^{k} \hat{R}_t(j) - k\mu\right]. \end{aligned} \tag{3.4}$$

The difference between the permanent component (S_t^P) and current value (S_t) is called *a transitory or cyclical component* and it is defined as

$$S_t^T = \lim_{k\to\infty}\left[\sum_{j=1}^{k} \hat{R}_t(j) - k\mu\right]. \tag{3.5}$$

It can also be written as

$$S_t^T = \left(\sum_{i=1}^{\infty} \psi_i\right)\varepsilon_t + \left(\sum_{i=2}^{\infty} \psi_i\right)\varepsilon_{t-1} + \ldots \tag{3.6}$$

The first differences of the permanent component is described as

$$S_t^P - S_{t-1}^P = \mu + \left(\sum_{i=0}^{\infty} \psi_i\right)\varepsilon_t, \ \psi_0 = 1. \tag{3.7}$$

The permanent component follows a random walk with the rate of drift μ. The transitory component in equation (3.5) is a stationary process with mean zero as long as the process R_t is well defined, having covariance-stationary structures. After identifying the ARMA(p,q) process for R_t, the algorithm derived by Newbold (1990) is used to compute the Beveridge-Nelson decomposition. First, I subtract the mean (μ) from the ARMA(p,q) process in (3.2).

$$\begin{aligned} Y_t &= R_t - \mu, \\ \hat{Y}_t(j) &= \hat{R}_t(j) - \mu, \end{aligned} \tag{3.8}$$

where $\hat{R}_t(j)$ is estimated from the Box-Jenkins procedure. The computation of the permanent and transitory components can be carried out as follows.

$$\begin{aligned} S_t^T &= \sum_{j=1}^{q} \hat{Y}_t(j) + \left(1 - \phi_1 - \ldots - \phi_p\right)^{-1} \sum_{j=1}^{p} \sum_{i=j}^{p} \phi_i \hat{Y}_t(q - j + 1), \\ S_t^P &= S_t + S_t^T. \end{aligned} \tag{3.9}$$

Next section provides empirical statistical distributions of both permanent and transitory components calculated from equation (3.9).

Section 2: Empirical Results

An autoregressive moving average (ARMA) representation for first-differences of each daily spot rate must be identified before the implementation of the Beveridge-Nelson decomposition.[20] Table 3.1 shows the ARMA models for percentage changes in daily spot rates during the sample period. For example, the ARMA representation of the German mark vis-a-vis the U.S. dollar is an ARMA (15,6) process. The selection of AR's and MA's terms is based on the absence of serial correlation in residuals using the Ljung-Box statistics with 24 degrees of freedom.[21] The ARMA estimation methodology is the Box-Jenkins procedure. Additional tests on autoregressive conditional heteroscedastic (ARCH) and normality are also implemented to provide a statistical description of the data. The ARCH tests indicate that the ARMA representation for each currency exhibits a high degree of heteroscedasticity. The Jarque-Bera normality tests suggest the rejection of the normality assumption for all currencies. Even though the presence of heteroscedasticity and non-normality may violate the assumptions underlying the Box-Jenkins and Beveridge-Nelson procedures, the data are treated as if they are intertemporally uncorrelated and homoscedastic and come from a normal distribution at this moment. I discuss this violation and propose a statistical model to accommodate heteroscedasticity and non-normality in the data in Section 6.

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[20]The Dickey-Fuller and Phillips-Perron tests suggest that all investigated currencies are integrated of order 1. As a result, they comply with the assumption underlying the Beveridge-Nelson decomposition technique. Non-stationary series can be decomposed into permanent and transitory components.
[21]The parsimonious approach is also employed to obtain the lowest possible AR's and MA's lags.

Table 3.1

ARMA Models of Log Price Changes of Daily Spot Rates

Statistics	DM	BP	FF	JY	SF	CD
Autoregressive terms	15	6	15	15	12	2
Moving average terms	6	2	0	0	3	5
Sample size	6418	6427	6418	6418	6421	6431
Ljung-Box(24) test	4.9035	24.1495	11.3814	12.0331	14.4994	18.6879
for serial correlation	(0.18)	(0.09)	(0.25)	(0.21)	(0.11)	(0.35)
ARCH(24) F-test	14.2829	22.0582	10.3477	14.5786	46.1742	19.6043
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Jarque-Bera	3915	4704	7936	5876	39904	4310
Normality test	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)

Table 3.2 presents descriptive statistics for the observed series in panel A, permanent components in panel B, and transitory components in panel C. The statistics include mean, standard deviation, skewness, kurtosis, and the Jarque-Bera asymptotic normality test. The observed series are raw data expressed in percentage changes in actual daily spot rates in Table 3.2 panel A. The British pound (BP), the French franc (FF), and the Canadian dollar (CD) depreciate, on average, against the U.S. dollar over the sample period. The German mark (DM), the Japanese yen (JY), and the Swiss franc (SF) appreciate vis-a-vis the U.S. dollar on average. The means of every exchange rate but the CD are statistically indifferent from zero. All currencies, except the CD, exhibit high degree of volatility. The Canadian dollar appears to be less volatile than other currencies due to, perhaps, the brisk mobility of goods and services between the U.S. and Canada, and thus quick and stable adjustment of the $/CD exchange rate.

With the exception of the DM, the tests for normal (zero) skewness can be rejected for every currency. There is a negative skew for the BP, FF, SF, and CD and a relatively large positive skew for the JY. The tests of normal skewness suggest the asymmetry of the probability distributions of percentage changes in daily spot rates. The skewness of the distributions of the BP, FF, JY, and CD is related to the trend value of the currencies (having the same signs). The skewness of the DM and SF is negative while both currencies appreciate vis-a-vis the U.S. dollar during the sample period. Unlike Calderon-Rossell and Ben-Horim (1982) findings, the results in this study suggest that the skewness shows no systematic pattern to the trend value of the currency.

All currencies exhibit leptokurtosis. Their distributions are more peaked and fat-tailed than the normal distribution. The tests for normal skewness and normal kurtosis indicate the rejection of the normality hypothesis. Non-normality is also confirmed by the Jarque-Bera Chi-squared tests.

Table 3.2 panel B presents descriptive statistics for the fundamental components (Beveridge-Nelson's permanent component). The results for mean, variance, and skewness are similar to those of the raw data. However, the permanent components show a higher degree of leptokurtosis than the observed series. Why are the fundamental components more peaked and fat-tailed than the observed series? This higher leptokurtosis can be illustrated by tracking back to the derivation of the Beveridge-Nelson decomposition.

Table 3.2

Summary Statistics of Log Price Changes of Daily Spot Rates for Observed Series, Permanent Components and Transitory Components

Panel A: Observed Series

Statistics	DM	BP	FF	JY	SF	CD
Sample size	6391	6411	6391	6391	6391	6411
Mean (hundreds)	0.0066	-0.0048	-0.0030	0.0114	0.0122	-0.0073
t-statistics(mean=0)	0.8225	-0.6217	-0.3824	1.4635	1.2838	-2.3247
	(0.41)	(0.53)	(0.70)	(0.14)	(0.20)	(0.02)
Standard deviation	0.6422	0.6151	0.6221	0.6232	0.7619	0.2501
Skewness	-0.0384	-0.1409	-0.1407	0.4696	-0.0622	-0.2015
	(0.21)	(0.00)	(0.00)	(0.00)	(0.04)	(0.00)
Kurtosis	3.7439	4.1826	5.4640	4.5680	12.4194	4.1266
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Jarque-Bera	3734	4694	7971	5791	ELN	4592
Normality test	(0.00)	(0.00)	(0.00)	(0.00)		(0.00)

Panel B: Permanent Components

Statistics	DM	BP	FF	JY	SF	CD
Sample size	6391	6411	6391	6391	6391	6411
Mean (hundreds)	0.0060	-0.0054	-0.0032	0.0113	0.0119	-0.0072
t-statistics(mean=0)	0.6686	-0.6804	-0.4521	1.7492	0.6066	-2.6132
	(0.50)	(0.50)	(0.65)	(0.08)	(0.54)	(0.01)
Standard deviation	0.7121	0.6319	0.5580	0.5161	1.5717	0.2214
Skewness	-1.6031	0.0734	-0.1205	0.4491	0.5331	-0.1573
	(0.00)	(0.02)	(0.00)	(0.00)	(0.00)	(0.00)
Kurtosis	66.6330	15.2471	4.9249	4.2258	69.6492	3.8243
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Jarque-Bera	ELN	ELN	6474	4970	ELN	3933
Normality test			(0.00)	(0.00)		(0.00)

ELN stands for Extremely Large Numbers.

Table 3.2 (Continued)

Panel C: Transitory Components

Statistics	DM	BP	FF	JY	SF	CD
Sample size	6391	6411	6391	6391	6391	6411
Mean (hundreds)	-0.0007	-0.0006	-0.0002	-0.0001	-0.0003	0.00004
t-statistics(mean=0)	-0.0675	-0.1579	-0.1242	-0.0701	-0.0169	0.0426
	(0.95)	(0.87)	(0.90)	(0.94)	(0.98)	(0.96)
Standard deviation	0.7723	0.3012	0.1161	0.1307	1.4678	0.0670
Skewness	-1.7346	2.9249	0.0207	-0.2464	1.2480	0.8952
	(0.00)	(0.00)	(0.50)	(0.00)	(0.00)	(0.00)
Kurtosis	54.0197	222.53	11.3744	5.1058	93.6892	70.2806
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Jarque-Bera	ELN	ELN	ELN	7006	ELN	ELN
Normality test				(0.00)		

ELN stands for Extremely Large Numbers.

If I assume that the exchange rate series is non-stationary and its first-differences follow the MA(1) process, it can be described as.

$$R_t = \mu + \varepsilon_t + \theta_1 \varepsilon_{t-1},$$

where θ_1 is a moving average parameter and $|\theta_1| < 1$ for a covariance-stationary structure. The first-difference of the permanent component is then

$$S_t^P - S_{t-1}^P = \mu + \left[(1+\theta)\varepsilon_t\right].$$

The variance of this component $(1+\theta_1)^2 \varepsilon_t^2$ will be larger than ε_t^2 if changes in S_t are positively correlated. The analysis of autocorrelations shows that percentage changes in daily spot rates are significantly positively autocorrelated.[22] Thus, the permanent components appear to be more volatile and more peaked and fat-tailed than the observed

[22]The analysis shows that the autocorrelations for the DM, BP, FF, JY, SF, and CD are 0.023, 0.053, 0.023, 0.029,0.003, and 0.062. With the exception of the SF, the autocorrelations are all significance at the 5 percent level. Liu and He (1991) also report positively significant serial correlations in weekly exchange rates.

series. The Jarque-Bera tests also indicate the rejection of the normality for all currencies.

Table 3.2 panel C shows statistical properties of the transitory components that represent, by the definition of Beveridge and Nelson (1981), deviations of exchange rates from long-run equilibrium values. The mean of the transitory components is statistically indistinguishable from zero. This evidence is consistent with the underlying assumption of zero mean (see equation (3.5)). According to the skewness test, only the transitory component of the French franc is symmetric. In general, the transitory component exhibits an even higher degree of leptokurtosis than the permanent component. This extreme kurtosis is expected. The transitory component represents exchange rates when they are too volatile to be accounted for by subsequent changes in fundamentals. Deviations (or outliers) from fundamentals may cause the distribution to be more peaked and fat-tailed. The rejection of the normality hypothesis is supported by the Jarque-Bera test.

Section 3: Time-Varying Means or Variances

The analysis in the previous section suggests that spot rate changes are more peaked and fat-tailed than a normal distribution and are asymmetrically distributed. One explanation of leptokurtosis (fat tail distribution) of changes in daily spot rates suggests that means and variances may change over time (e.g., Calderon-Rossell and Ben-Horim (1982), Friedman and Vanderstell (1982), and Hsieh (1988)). To test for time-varying means and variances for spot rate changes, I use the Mann-Whitney U test, a rank-based nonparametric test for comparing the location of two populations using independent samples.[23] The Mann-Whitney U test is a distribution-free statistic and it is appropriate in this study since the correct form of the distribution of spot rate changes is unknown.[24] The Mann-Whitney test uses a stationary property of parameter values estimated from the data. If probability distribution between consecutive subperiods is stationary, estimated parameters (i.e., mean and variance) from past data will be statistically consistent with parameter values in the future period.[25]

To test for equality of the two subsequent distributions, the 24-year sample period between February 1, 1974 and August 31, 1998 (6411 observations) is divided into eight different periods of approximately 3 years each.[26] The partitioning of the data is arbitrary to obtain enough subperiods for comparison and a large number of observations in each subperiod for reliable statistical inference.[27] Eight subperiods are (I) February 1974-December 1982, (II) January 1977-December 1979, (III) January 1980-December 1982, (IV) January 1983-December 1985, (V) January 1986-December 1988, (VI) January 1989-December 1991, (VII) January 1992-December 1994, and (VIII) January 1995-August 1998. For each subperiod, the first observation is the first trading day of the beginning month (usually January 2nd) and the last observation is the last trading day of the ending month (usually December 31st).

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[23]It is also referred to as the Wilcoxon two-sample test. Let *F(x)* and *G(y)* be the distribution functions of X and Y, respectively. The null hypothesis is $F(z)=G(z)$ for all z and the alternative hypothesis is either $F(z)>G(z)$ or $F(z)<G(z)$ for all values of z (see Hogg and Graig (1978, pp. 326-327)).
[24]Hsieh (1988) uses a Chi-square test in which the alternative is *F(z) is not equal to G(z)*. I follow Calderon-Rossell and Ben-Horim (1982) approach.
[25]The Mann-Whitney test assumes that the parameters are constant within each subperiod.
[26]The total sample is reduced from 6433 observations due to the use of lags in implementing the Beveridge-Nelson decomposition. See the sample size row in Table 3.2 for a number of observations for each currency.
[27]Calderon-Rossell and Ben-Horim (1982) use 3 two-year subperiods.

Table 3.3 reports the Mann-Whitney U statistics for the null hypothesis that probability distributions do not change from subperiod i to subperiod j. In general, the distributions of changes in spot rates vary at least once between consecutive subperiods (panel A). The distribution of each exchange rate shifts between subperiod IV (1983-1985) and subperiod V (1986-1988), the periods of the over- and under-valued dollars. The U.S. dollars exhibited larger swings in those years. The distribution of spot rate changes also varies between subperiods II and III, with the exception of the Canadian dollar. Rejections of the stationarity hypothesis also occur for some consecutive subperiods for certain currencies.

Table 3.3 shows that the shifts in the distribution of spot rate changes are due solely to the shift of parameters in the fundamental components. The rejection of the null hypothesis of stationarity in panel B is similar to that of panel A, especially during subperiods IV and V. The transitory components are stationary over time as by definition (panel C). Temporary deviations revert back to the long-run equilibrium value. Non-fundamental components die out over time.

Table 3.3

Mann-Whitney U Statistics for Stationarity of the Distributions of Changes in Daily Spot Rates

Panel A: Observed Series

Subperiod Comparison	Currencies					
	DM	BP	FF	JY	SF	CD
I and II	1.6222	3.7691**	2.0273**	1.5304	1.3120	1.9673**
II and III	3.8486**	2.6919**	4.1563**	1.9286*	3.3457**	1.3471
III and IV	0.8699	0.0515	1.2505	1.6325	0.7979	0.9167
IV and V	2.3460**	2.3924**	1.9968**	2.4119**	2.0760**	3.8843**
V and VI	0.8172	0.6132	0.4347	2.7328**	1.3863	0.6189
VI and VII	0.1708	0.2357	0.2040	1.5367	1.0497	3.1231**
VII and VIII	1.3762	0.1942	1.6199	2.7515**	1.7723*	0.9799

Panel B: Permanent Components

Subperiod Comparison	Currencies					
	DM	BP	FF	JY	SF	CD
I and II	0.9718	4.1837**	2.2103**	1.6971*	0.3233	2.1134**
II and III	4.6141**	2.9193**	4.4704**	2.2679**	2.1406**	1.5513
III and IV	1.1010	0.0840	1.3552	1.7465*	0.2760	1.3410
IV and V	2.8929**	2.2229**	2.2255**	2.5810**	1.9268*	4.4710**
V and VI	1.0791	0.7792	0.4014	3.1431**	1.3010	0.9599
VI and VII	0.5701	0.4224	0.0291	1.6534*	0.8714	3.4678**
VII and VIII	1.8293*	0.1152	1.6973*	3.2635**	1.7100*	1.0818

Panel C: Transitory Components

Subperiod Comparison	Currencies					
	DM	BP	FF	JY	SF	CD
I and II	1.0459	0.3726	0.3568	0.1334	0.1411	0.2812
II and III	0.7223	0.0235	0.7490	0.6434	0.7664	0.2145
III and IV	0.2183	0.2473	0.2190	0.4148	0.3618	0.0635
IV and V	0.1602	0.2943	0.2954	0.6293	0.2186	0.0208
V and VI	0.5632	0.2552	0.7359	0.8512	0.2824	0.2023
VI and VII	1.1250	0.8699	1.1995	0.8076	0.0615	0.0482
VII and VIII	0.4693	0.9444	0.5658	0.2418	0.0350	0.0333

(*) and (**) denote significant at 10% and 5% levels, respectively.

The non-stationarity of the distribution of changes in spot rates may be the result of changes in either mean, variance, or both. To examine the stationarity property of the mean, each currency is centered by subtracting its mean. The results in Table 3.4 suggest that changes in means cannot account for the rejection of parameter-stationarity hypothesis. Means appear to be stable for all two subsequent subperiods.[28]

Each currency is scaled by dividing its standard deviation to check stationarity in variance. Table 3.5 presents the results of test of equality in variances. With the assumption that variances are constant within each subperiod, changing variances between two consecutive subperiods appear to be responsible for the non-stationary distribution of changes in spot rates. Similar to the results in Table 3.3, the fundamental components appear to be the source of changes in the variances. The periods of high and unstable volatilities are between 1974-1976 and 1977-1979, between 1977-1979 and 1980-1982, and between 1983-1985 and 1986-1988.

In summary, the analysis shows that distributions of spot rate changes vary over time due to changes in variances of the permanent components. In the next section, I examine how these empirical results are relevant to the Efficient Market Hypothesis.

[28]The only exception is the British pound between subperiods I and II. The test statistic is significant at the 5 percent level, implying the non-stationarity in the mean between the two subperiod.

Table 3.4

Mann-Whitney U Statistics for Stationarity of Means of the Distributions of Changes in Daily Spot Rates

Panel A: Observed Series

Subperiod Comparison	Currencies					
	DM	BP	FF	JY	SF	CD
I and II	0.2385	1.9843**	0.0745	0.3384	0.3149	0.3377
II and III	0.5428	0.6208	0.0875	1.1494	0.7951	0.1205
III and IV	0.3678	0.9051	0.5645	0.9357	0.0658	0.0318
IV and V	0.8451	0.9077	0.5927	0.5565	0.7457	0.0264
V and VI	0.0926	0.2548	0.1378	0.5147	0.6533	0.7312
VI and VII	0.3629	0.1619	0.4572	0.2342	0.8224	0.6459
VII and VIII	0.5335	0.9680	0.8828	0.1844	0.8439	0.3353

Panel B: Permanent Components

Subperiod Comparison	Currencies					
	DM	BP	FF	JY	SF	CD
I and II	0.4464	1.2726	0.2052	0.3401	0.0131	0.3239
II and III	0.0696	0.6833	0.2853	1.2645	0.0952	0.3065
III and IV	0.6399	0.7597	0.6047	0.9625	0.3841	0.2344
IV and V	0.8250	0.8482	0.6962	0.5361	0.6599	0.1759
V and VI	0.1046	0.1872	0.0492	0.4130	0.5675	0.6733
VI and VII	0.1114	0.0360	0.3347	0.1542	0.7551	0.6418
VII and VIII	0.6817	0.9566	0.8885	0.1524	0.6929	0.3144

Panel C: Transitory Components

Subperiod Comparison	Currencies					
	DM	BP	FF	JY	SF	CD
I and II	1.3008	1.4686	0.6304	0.0308	0.1952	0.2583
II and III	0.7574	0.0833	0.7208	0.7965	0.6849	0.1932
III and IV	0.2046	0.2838	0.1741	0.7203	0.0261	0.0226
IV and V	0.2508	0.3304	0.3574	0.4948	0.1509	0.1224
V and VI	0.5380	0.1570	0.7208	0.8475	0.5340	0.1333
VI and VII	0.8458	0.6495	0.8478	0.6767	0.3044	0.0687
VII and VIII	0.2429	0.7767	0.2918	0.2254	0.1038	0.1856

(*) and (**) denote significant at 10% and 5% levels, respectively.

Table 3.5

Mann-Whitney U Statistics for Stationarity of Variances of the Distributions of Changes in Daily Spot Rates

Panel A: Observed Series

Subperiod Comparison	Currencies					
	DM	BP	FF	JY	SF	CD
I and II	1.5165	3.6902**	1.8632*	1.9724**	0.9559	1.8595*
II and III	3.8962**	2.9479**	4.1596**	1.8363*	3.3843**	1.4361
III and IV	0.8699	0.2115	1.2099	1.0419	0.3690	1.0511
IV and V	2.3331**	2.3646**	1.9765**	2.2679**	2.0780**	3.7780**
V and VI	0.8438	0.7251	0.4581	2.7207**	1.3869	0.1895
VI and VII	0.1931	0.1885	0.2256	1.5194	1.0533	3.2434**
VII and VIII	1.4284	0.0059	1.6888*	2.5536**	1.7589*	0.8927

Panel B: Permanent Components

Subperiod Comparison	Currencies					
	DM	BP	FF	JY	SF	CD
I and II	3.0897**	4.4597**	2.2171**	1.8801*	0.8384	2.1485**
II and III	4.7297**	3.0509**	4.4469**	2.1533**	2.2072**	1.6959*
III and IV	1.6770*	0.2237	1.2976	1.1952	0.1138	1.5243
IV and V	2.8570**	2.3056**	2.1926**	2.3798**	1.9407*	4.3104**
V and VI	0.9692	0.9327	0.4214	3.1179**	1.3021	0.4844
VI and VII	0.4283	0.3715	0.0049	1.6353	0.8761	3.5872**
VII and VIII	1.8279*	0.0753	1.7823*	3.0436**	1.7291*	1.0300

Panel C: Transitory Components

Subperiod Comparison	Currencies					
	DM	BP	FF	JY	SF	CD
I and II	1.3131	0.2657	0.7055	0.2022	0.2900	0.1159
II and III	0.8102	0.2538	0.8631	0.6408	0.4259	0.2127
III and IV	0.0865	0.0236	0.2752	0.0037	0.3481	0.0545
IV and V	0.1423	0.1476	0.3008	0.6574	0.2944	0.0382
V and VI	0.5378	0.2012	0.6996	0.8623	0.2860	0.2340
VI and VII	1.0429	0.8930	1.1446	0.7505	0.0545	0.0523
VII and VIII	0.4254	0.8245	0.5611	0.2280	0.1053	0.0020

(*) and (**) denote significant at 10% and 5% levels, respectively.

Section 4: Market Efficiency Views

The analysis thus far indicates that the observed exchange rates may have non-normal distributions or normal distributions with non-stationary variance (due to the volatility of fundamental components). Surajaras and Sweeney (1992) discuss two alternative views based on the stock-market literature. The first view is that exchange rates are drawn from a normal distribution with nonstationary variances. Another view is that exchange rates contain discrete jumps due to, perhaps, government intervention, market overreaction, or fads. If these discrete jumps occur uniformly around the mean, exchange rates may follow a mean reverting process. This process can create a shift in the scaling parameter of the distribution.

Which of the alternative views is applicable? Both hypotheses are not mutually exclusive. For example, if foreign-exchange investors overreact to the announcement of macroeconomic news in some periods, there will be discrete jump in the exchange rates. These occasional jumps will cause the exchange rates to be more volatile than may be justified by changes in the fundamentals, causing the returns variance in those periods to be different from that of other periods. The market overreaction can create a shift in the parameters of the distribution and both views are valid.

Surajaras and Sweeney (1992) propose a method to indirectly test both hypotheses. Using the rule of stability under addition, monthly average returns should have similar statistical properties as the daily returns data. For instance, if the true population distributions of daily spot rates are non-normals, the monthly averages should belong to the non-normal distributions as well.

The Jarque-Bera normality tests in Table 3.6 show that the normality assumption can be rejected for monthly average returns for all currencies. However, the degrees of leptokurtosis in both permanent and transitory components decline. Tables 3.7 and 3.8 present the Mann-Whitney U tests on the null hypotheses of stationary means and variances.[29] The results in Table 3.7 support the previous analysis that means are stationary over time. With the exception of few cases, monthly returns variances appear to be stationary as well.

The stationarity of variances in monthly average returns implies that the nonstationary variances in daily returns exhibit a non-systematic pattern. They are averaged out over calendar months. For example, if market overreaction or government intervention occurs randomly and thus creates an irregular discrete jump, the scaling parameter of the distribution will shift accordingly. Since there will be no pattern in the nonstationarity of the parameter, on average and over time, stationarity of the parameter is expected. In addition, nonstationary variances in daily data may be due to the day-of-the-week effect (e.g. Hsieh (1988)). This nonstationarity effect in daily data should disappear in monthly averages.

[29]The analysis focuses only on the observed series and permanent components. Since the transitory components, by definition, are stationary with mean zero, the results are similar to those shown in Tables 3.4 panel C and 3.5 panel C.

Table 3.6

Summary Statistics of Monthly Average Rates of Returns for Observed Series, Permanent Components and Transitory Components

Panel A: Observed Series

Statistics	DM	BP	FF	JY	SF	CD
Sample size	294	295	294	294	294	295
Skewness	-1.0223	0.6577	-0.1570	0.3517	-0.7541	-0.2328
	(0.00)	(0.00)	(0.27)	(0.01)	(0.00)	(0.10)
Kurtosis	4.3459	7.2623	3.0410	2.2031	15.7975	4.7211
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Jarque-Bera	282	669	114	65	3084	276
Normality test	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)

Panel B: Permanent Components

Statistics	DM	BP	FF	JY	SF	CD
Skewness	0.5276	-0.6224	-0.1570	-0.0313	1.8255	0.1278
	(0.00)	(0.00)	(0.27)	(0.83)	(0.00)	(0.37)
Kurtosis	3.2945	3.5337	3.0410	8.4039	21.6157	1.3966
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Jarque-Bera	146	172	114	865	5887	24
Normality test	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)

Panel C: Transitory Components

Statistics	DM	BP	FF	JY	SF	CD
Skewness	0.3885	-1.1090	-0.2147	-0.7541	-0.1490	0.1562
	(0.01)	(0.00)	(0.13)	(0.00)	(0.30)	(0.27)
Kurtosis	2.8253	7.1286	4.4327	15.7975	3.6622	0.9167
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Jarque-Bera	105	685	243	931	165	11
Normality test	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)

Table 3.7

Mann-Whitney U Statistics for Stationarity of Means of Monthly Average Rates of Returns

Panel A: Observed Series

Subperiod Comparison	Currencies					
	DM	BP	FF	JY	SF	CD
I and II	0.8108	0.1610	0.0823	0.2233	0.0705	0.0920
II and III	0.4730	0.1689	0.0901	0.1014	1.1375	0.0338
III and IV	0.3041	0.3153	0.1915	0.1352	0.4054	0.0113
IV and V	0.1915	0.2590	0.9123	0.6870	0.1239	0.2816
V and VI	1.3740	0.1464	0.7433	0.7208	0.1577	0.7658
VI and VII	0.3604	0.0450	0.4730	0.6532	0.2703	1.2276
VII and VIII	0.0193	0.7157	1.2476	0.2224	0.3482	0.5416

Panel B: Permanent Components

Subperiod Comparison	Currencies					
	DM	BP	FF	JY	SF	CD
I and II	0.1410	0.2300	0.9871	0.6463	0.1293	0.1495
II and III	0.7658	0.5631	0.4167	0.4730	0.0338	0.1915
III and IV	0.6983	0.3491	0.3829	1.4528	0.3717	0.4955
IV and V	0.1577	0.4054	0.4843	1.0249	0.0113	0.1464
V and VI	0.8897	0.7546	0.1352	0.6307	0.1802	0.3153
VI and VII	0.4843	0.4054	1.3627	0.1689	0.3491	0.7433
VII and VIII	0.1161	0.0677	1.3830	0.0097	0.8704	0.6480

(*) and (**) denote significant at 10% and 5%, respectively..

Table 3.8

Mann-Whitney U Statistics for Stationarity of Variances of Monthly Average Rates of Returns

Panel A: Observed Series

Subperiod Comparison	Currencies					
	DM	BP	FF	JY	SF	CD
I and II	1.0223	0.5176	0.1058	1.0693	0.5405	0.2300
II and III	0.8672	0.5856	0.5406	0.4167	1.1488	0.5068
III and IV	0.6420	1.1037	0.5181	0.2140	1.0587	0.5969
IV and V	0.3266	1.1488	1.2389	1.4191	0.3829	0.1577
V and VI	0.9123	0.2140	1.6893*	1.4078	0.1802	0.9460
VI and VII	0.8785	0.4167	2.0272**	1.1488	0.2928	0.5631
VII and VIII	0.1547	0.2901	0.7060	0.3675	0.6963	0.5706

Panel B: Permanent Components

Subperiod Comparison	Currencies					
	DM	BP	FF	JY	SF	CD
I and II	0.1528	0.1955	3.5612**	0.5523	0.4465	0.8511
II and III	0.7208	1.0699	4.0995**	1.4528	0.0450	0.4618
III and IV	0.4392	1.5542	0.7208	1.4979	0.3041	1.2276
IV and V	0.9911	2.9620**	0.3829	1.4303	1.3965	0.8559
V and VI	1.2051	0.2027	1.0136	0.3491	0.8447	0.6870
VI and VII	0.4955	0.9686	1.0249	0.7546	0.1126	1.2614
VII and VIII	0.0484	0.4545	0.0774	0.0870	0.0774	1.4120

(*) and (**) denote significant at 10% and 5%, respectively.

Daily spot rates may contain discrete jumps. These jumps occur on an irregular basis such that, by taking monthly averages, the effect of these jumps in daily data declines. The evidence is reduced leptokurtosis and stationary variances in monthly average returns. Exchange rates may contain a component that cannot be explained by changes in fundamentals, i.e., relative prices and interest rates. I define this non-fundamental component to be a transitory component. In the definition of Beveridge and Nelson (1981), the transitory component is a deviation of an exchange rate from its long-run equilibrium value that reflects a fundamental value of exchange rates justified by rational expectations of economic agents. Several exchange-rate studies support the view that exchange rates may contain discrete jumps. Adler and Dumas (1983) and Akgiray and Booth (1988), for example, propose a mixed diffusion-Poisson process to explain exchange rate movements.

Note that the analysis does not completely rule out the hypothesis that exchange rates may come from a normal distribution with time-varying variances. The shifts in variances may occur within calendar months such that, on monthly average, variances are stationary. The time-varying risk view in exchange rates is supported by several studies (e.g., Fama (1984) and Bollerslev, Chou and Kroner (1992) for a survey). Recent studies commonly use the (G)ARCH process to model changes in daily spot rates. I employ the ARCH modeling in the next section.

Section 5: A Statistical Model

After analyzing statistical properties of daily spot rates, this section attempts to identify a class of data-generating processes based on these statistical properties. To incorporate both market efficiency views of daily spot rates discussed in the previous section, I model the logarithm of daily spot rates (S_t) as the sum of a permanent component (S_t^P) and a transitory component (S_t^T) as[30]

$$S_t = S_t^P + S_t^T. \tag{3.10}$$

[30] I use a fads model proposed in Summers (1986) and Poterba and Summers (1988). They model stock prices as the sum of a random walk process and an AR(1) process. I, however, allow innovations to the permanent and transitory components to be perfectly correlated and time-varying. There is only one type of shock in the exchange rate economy. This shock will have both permanent and temporary effects.

The permanent component is assumed to follow a random walk process with dependent but uncorrelated increments as[31]

$$S_t^P - S_{t-1}^P = \varepsilon_t. \tag{3.11}$$

The transitory component is a mean-stationary AR(1) process with time-varying variance and is defined as[32]

$$S_t^T = \rho S_{t-1}^T + \varepsilon_t, \tag{3.12}$$

where ρ is the first-order autocorrelation. It is also a measure of the persistence of the transitory component. Both the permanent and transitory components are assumed to have zero means without loss of generality.[33] The error terms in (3.11) and (3.12) are assumed to follow a stochastic process of the form

$$\begin{aligned} \varepsilon_t &= v_t \sqrt{h_t}, \\ v_t &\overset{iid}{\sim} N(0,1), \end{aligned} \tag{3.13}$$

where h_t is a time-varying conditional variance and it follows the generalized ARCH or GARCH (1,1) process.[34]

$$h_t = \alpha_0 + \alpha_1 \varepsilon_{t-1}^2 + \beta h_{t-1}, \tag{3.14}$$

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[31]I include an ARCH error because studies over the last 15 years have shown that high-frequency economic time series exhibit non-constant variances. The time-varying variance is the result of persistence of the economic dynamic. For example, the persistence in the conditional variance may arise when "economic time" and "calendar time" do not correspond (Diebold and Lopez (1995)). When the underlying variance changes over time and is conditional on past forecast errors, the conventional econometric models are not applicable. Engle (1982) introduces an autoregressive conditional heteroscedastic (ARCH) process to account for non-constant conditional second moments in economic time series. The ARCH model and its derivatives are widely used in modeling time-varying volatilities in financial time series (see Bollerslev, Chou, and Kroner (1992) for a survey).

[32]The AR(1) process is assumed for simplicity. A model for both fads and time-varying expected returns proposed by, e.g., Fama and French (1988) and Poterba and Summers (1988) is the sum of a random walk and a *general* AR(p) process, where *p* is the autoregressive lags.

[33]The analysis from Table 3.2 shows that, in general, the means of both components are statistically indistinguishable from zeros.

[34]The GARCH(1,1) process is chosen because it is widely acknowledged to account for heteroscedasticity in the daily spot rates (see Bollerslev, Chou, and Kroner (1992) for a survey).

where α_0 is an intercept term and α_1 and β are autoregressive and moving average parameters for the variance equation. The following regularity conditions are imposed: $\alpha_0>0$, $\alpha_1\geq 0$ and $\beta\geq 0$. I also assume that the roots of $1-\beta Z=0$ lie outside the unit circle.

The permanent component (as well as the transitory component) has uncorrelated increments but is not independent: $\operatorname{cov}(\varepsilon_t,\varepsilon_{t-k})=0, \forall k\neq 0$ but $\operatorname{cov}(\varepsilon_t^2,\varepsilon_{t-k}^2)\neq 0, \forall k\neq 0$. An alternative view of the process in (3.11) is that it is consistent with the martingale property. The martingale hypothesis states that $E(\Delta S_t|\Omega_t)=0$ where Δ is the first-difference operator and W$_t$ is the information set at time t. The theory only states that changes in the mean are unpredictable; but, it does not rule out the possibility that higher moments, such as $E(S_t^2|\Omega_t)$, might depend on past S's (Baillie and Bollerslev (1989b)). Therefore, the permanent component is the random walk with dependent but uncorrelated increments.

When the permanent component and transitory component follow the processes as in equations (3.11) and (3.12) respectively, changes in daily spot rates $R_t=(S_t-S_{t-1})$ will follow an AR(1) process with GARCH(1,1) errors as[35]

$$R_t=\mu+\phi R_{t-1}+\varepsilon_t, \tag{3.15}$$

where μ is the long-run equilibrium value and ϕ is the first-order autocorrelation coefficient. The relationship between ρ and ϕ is that $\rho=\phi^2(1-\phi)^{-1}$.

[35]The derivation is shown in the Appendix.

I postulate that exchange rates have a conditional normal distribution. I incorporate ARCH errors to account for time-varying variance and allow the exchange rates to have a transitory component to account for possible occasional discrete jumps.[36] Table 3.9 presents estimated parameters for a proposed fads model in equation (3.15). After incorporating the ARCH errors, the ARCH effect in the data, based on the F-test, becomes statistically insignificant. The Ljung-Box test statistics on the squared residuals indicate no second-order dependency.[37] Estimated values for α_l's and β's are all statistically significant. The GARCH(1,1) model seems to capture time-varying variances.

The estimated ϕs for the DM, BP, JY, SF, and CD are 0.0195, 0.0474, 0.0332, 0.0308, and 0.049, respectively. These values imply that the first-order autocorrelations (r) of the transitory components of the DM, BP, JY, SF, and CD are 0.0004, 0.0024, 0.0011, 0.001, and 0.0025 per day, respectively. The persistence and magnitude of the non-fundamental components of these currencies are small. The currency movements may be largely due to the fundamental component.

The implied value of ρ for the FF is not available since the estimated value of f is not statistically indifferent from zero. The AR(1)-GARCH(1,1) seems to provide unsatisfactory empirical performance for the FF and JY during the sample period. The AR(1) model may not be a proper process for the transitory component and thus the mean equation of the FF. The GARCH(1,1) may not be a correct specification of the

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[36]One may posit that exchange rates come from a non-normal distribution. An alternative error distribution, i.e., the Standardized t-distribution can be assumed (Bollerslev (1987) and Baillie and Bollerslev (1989)).
[37]The exception is the Japanese yen. Additional AR and MA terms in the variance equation can be added to reduce the ARCH effect and thus the degree of second-order dependency.

variance equation of the JY. The search for a better statistical model of these currencies is left for future research.[38]

Table 3.9

Parameters Estimated from the AR(1)-GARCH(1,1) Model with the Normal Distribution

Diagnostic Statistics	Currencies					
	DM	BP	FF	JY	SF	CD
μ	0.0031	-0.0032	0.0025	0.0061	-0.0026	-0.0048
	(0.64)	(0.62)	(0.66)	(0.33)	(0.72)	(0.04)
ϕ	0.0195	0.0474	0.0120	0.0332	0.0308	0.0490
	(0.14)	(0.00)	(0.36)	(0.01)	(0.02)	(0.00)
α_0	0.0053	0.0045	0.0035	0.0014	0.0064	0.0013
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
α_1	0.0830	0.0651	0.1040	0.0574	0.0817	0.1029
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
β	0.9083	0.9251	0.8976	0.9430	0.9125	0.8831
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
$\alpha_1+\beta$	0.9913	0.9902	1.0016	1.0004	0.9942	0.9860
Implied ρ	0.0004	0.0024	N/A	0.0011	0.0010	0.0025
Skewness	0.0905	-0.0476	-0.1399	0.6328	-0.1901	-0.2707
Kurtosis	5.1821	9.2605	7.4808	7.5995	9.5320	5.8448
ARCH(20)	1.2975	0.4595	0.8290	1.7876	0.7348	0.8578
F-test	(0.17)	(0.98)	(0.68)	(0.02)	(0.79)	(0.64)
Ljung-Box(20)	26.4004	9.3772	16.4637	35.5796	15.3890	17.2919
Q test	(0.12)	(0.97)	(0.63)	(0.01)	(0.70)	(0.57)
Log-likelihood	-5719.72	-5368.07	-5425.86	-5415.44	-6749.73	307.43

N/A denotes the non-availability of an implied measure of the persistence of the transitory component. This is due to a statistically insignificant AR parameter in the mean equation.

[38]This statistical exercise is not employed in this study. The AR(1)-GARCH(1,1) is proposed based on previous studies of fads, e.g., Summers (1986). In addition, daily spot rates may contain day-of-the-week effect as in Hsieh (1988). Incorporating weekday dummy variables may improve the empirical performance.

Note that the estimated values for $\alpha_1+\beta$ for all currencies are close to one. An Integrated GARCH of IGARCH(1,1) may be applicable. I do not attempt to use the IGARCH model because the unconditional variance may not exist when $\alpha_1+\beta = 1$(e.g., Bollerslev (1987)). Infinite variance may cause a statistical problem for the maximum likelihood estimation.

Section 6: Conclusion

The results show that percentage changes in daily spot rates are not normally distributed. Their distributions are more peaked and fat-tailed than a normal distribution. Further analysis suggests that distributions of changes in spot rates vary over time due to changes in variance of the fundamental component. The appraisal of the non-fundamental component implies deviations from long-run equilibrium exchange rates. The results can be reconciled with two market efficiency views that (1) exchange rates may be drawn from a normal distribution with time-varying variance and (2) exchange rates may contain discrete jumps due to, i.e., market overreaction or government intervention.

Based on statistical properties of spot rate changes, I model the logarithm of daily spot rates as the sum of a random walk and an AR(1) process as in Summers (1986). I allow conditional variances of the two processes to be time-varying, having ARCH errors. I propose an AR(1)-GARCH(1,1) model to describe statistical characteristics of exchange rates in this study. The model is able to capture non-stationary variances for all currencies. In certain aspects, the model is not able to account for leptokurtosis in spot rates. Alternative variance specifications, i.e., the exponential GARCH, and alternative error distributions, i.e., the generalized error distribution, may be able to account for the leptokurtosis in the data and provide better empirical performance. The search for an appropriate statistical model is left for future research.

CHAPTER 4

RELATIVE STRENGTH STRATEGIES

The foreign exchange (FX) market is one of the most active financial markets. In 1995, the average trading volume was approximately $1.2 trillion per day (Bank for International Settlements (1996)). The sheer volume in this market has captured the attention of researchers examining speculative efficiency in the FX market. If the market processes information efficiently and exchange rate movements follow a random walk model, price changes should exhibit zero serial correlation and, as such, speculation based on past price movements should not consistently be profitable. However, if the market is informationally inefficient and exchange rate changes show some regularities, it may be possible to earn significant profits using trading rules based on historical price movements.

Many exchange rate studies have documented that changes in exchange rates are not serially independent.[39] For example, Engel and Hamilton (1990) contend that the dollar appears to exhibit long swings in one direction for certain periods of time. They propose the long swings hypothesis as an alternative to the random walk hypothesis. A long swing in one direction of exchange rates implies positive serial correlations and thus creates a kind of "momentum" in the series. If exchange rates persistently swing away from their fundamental values by exhibiting long periods of depreciation and appreciation (i.e., the dollars in the 1980s, as shown in Figure 1), a trading strategy of buying as the currency value rises and selling as it falls should generate profits. The trading strategy that captures price movement continuation (or price momentum) is referred to as *the relative strength strategy*. The relative strength strategy is commonly used in the stock market literature to examine the Efficient Markets Hypothesis (EMH).[40]

One implication of market efficiency is that speculators using mechanical trading rules can not consistently make excess profits. Previous works on trading rules and FX market efficiency focus primarily on technical analysis, namely, filter rules. Cornell and Dietrich (1978), Logue, Sweeney and Willet (1978), Dooley and Shafer (1983), Sweeney (1986) among others provide evidence of speculative profits on individual currencies in the spot FX markets.[41] For example, Sweeney (1986) finds filter rule profits of daily spot rates during the 1973 to 1980 period. Surajaras and Sweeney (1992) provide detailed discussions of speculation in the FX markets and show that speculating on portfolios of currencies and on currency indexes is profitable.[42] Levich

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[39] Pioneer works of serial correlation tests in the FX markets are, for example, Poole (1967), Burt, Kaen and Boothe (1977). Recent studies, such as Liu and He (1991), using recent developed techniques also find serial dependency in exchange rates.

[40] The strategy buys stocks that have performed well in the past and sell stocks that have performed poorly in the past. Recent empirical works, i.e., by Jegadeesh and Titman (1993) and Rouwenhorst (1998) show that the strategy generates significant positive returns. Their results are inconsistent with the joint hypothesis of market efficiency and commonly used asset pricing models.

[41] With the exception of the study by Sweeney (1986), a common drawback from these studies is that they do not provide a sound measure of statistical significance of the results.

[42] For example, Surajaras and Sweeney (1992) show that an equally weighted portfolio of 15 major currencies provides average risk-adjusted returns of 3.4% per year during the period 1978-1982.

and Thomas (1993) present evidence of profitability in the currency futures markets. The results from these studies call into question the premise of the EMH.[43]

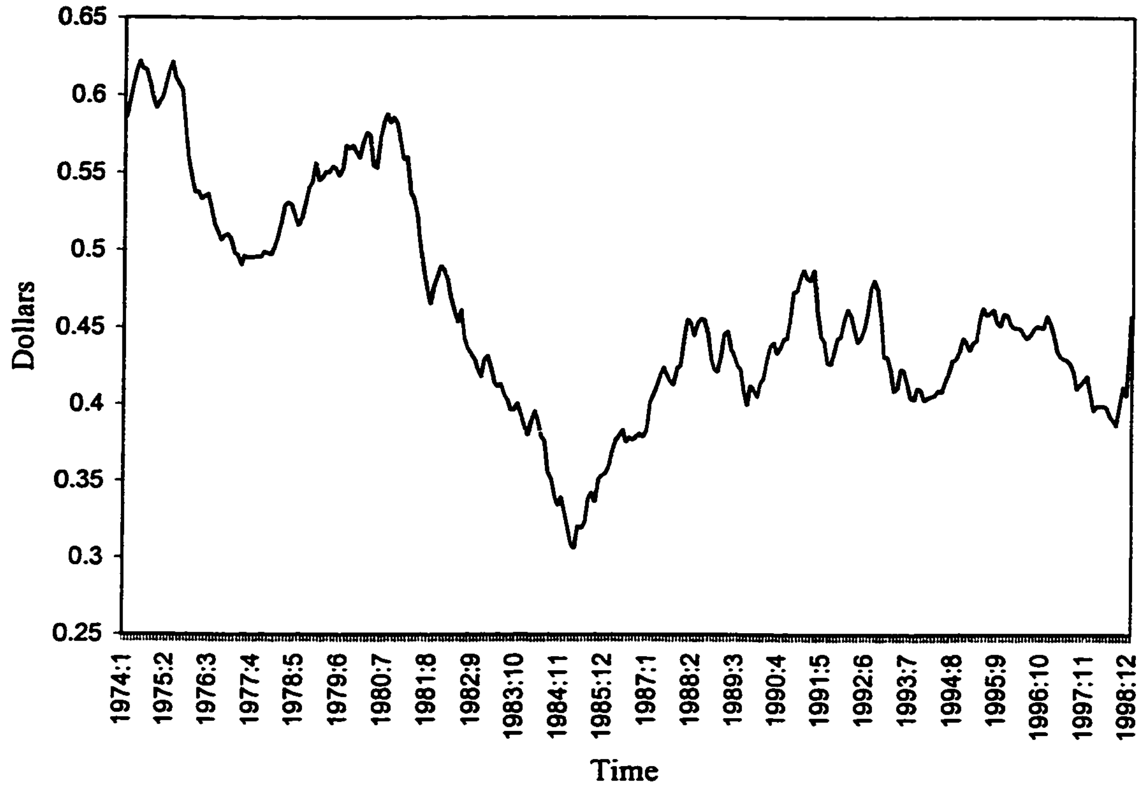

Figure 1: Twenty-One Country Equally-Weighted Exchange Rates

[43] Levich (1989) provides a survey of studies testing the efficiency of the foreign exchange markets.

The purpose of this study is to examine FX market efficiency using the relative strength investment strategy. As mentioned above, previous exchange rate studies commonly use filter rules, often resulting in "selection bias." Filter rules attempt to select winners while rejecting losers. By allowing sufficient computer time, profitable mechanical trading rules may be found (Jensen and Benington (1970)). This study avoids the selection bias by deriving trading strategies in advance and then applying them to the data. This study also considers returns on portfolios of currencies rather than returns on individual currencies as in most previous FX studies.[44] Forming portfolios of currencies may help reduce returns variability in a single currency and thus provide more reliable statistical tests. The currency portfolios formed in this study are equally weighted.[45] In addition, this study investigates short-term and medium-term returns using monthly data. Previous technical analysis studies of the FX market efficiency mainly focus on very short-term returns using daily spot rates. The presence of significant positive excess returns from daily data may be partly due to short-term price pressure from bid-ask spreads. The bid-ask spreads may create a significant upward bias in average returns calculated with transaction prices (Blume and Stambaugh (1983)). This study alleviates the bid-ask pressure by using longer returns interval and allowing one month lag between the portfolio formation period and the holding period.

Preliminary analysis of 21 currencies studied shows significant positive first-order autocorrelations for all currencies in the 1974 to 1998 sample period, thus implying a

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[44] The exception is the study by Surajaras and Sweeney (1992). They consider speculative profits on portfolios of currencies as well.

[45] The covariances of currencies in some portfolios and for some holding periods may be substantially positive, causing portfolio returns variabilities to be high. Positive cross-correlation among currencies will cause estimated standard errors to be higher and thus biased in favor of the null hypothesis.

certain degree of predictability of exchange rate changes. The analysis of relative strength strategies over 3 to 12 month holding periods documents statistically significant positive returns for each of the strategies examined. The positive returns persist even after they are adjusted for interest rate differentials. However, when excess returns are adjusted for a constant risk premium derived in a capital asset pricing model framework, the risk-adjusted excess returns are statistically indistinguishable from zero and, in some cases, are negative. The results in this study suggest that excess returns are the result of compensation for risks, not that of market inefficiency. The study finds evidence in support of the joint hypothesis of market efficiency and a constant risk premium.

This chapter is organized as follows. Section 1 describes the data used in this study. Section2 provides the preliminary analysis of the data. Section 3 describes relative strength trading strategies. Section 4 presents monthly average returns from the strategies. Section 5 adjusts raw returns for interest rate differentials. I show the results of risk-adjusted excess returns in section 6. Section 7 concludes with a summary of the results and a discussion of the study's implications regarding market efficiency.

Section 1: Data

The study covers the period from January 1974 through December 1998. The exchange rate and interest rate data are obtained from *the International Financial Statistics* (IFS) monthly bulletin. Twenty-one currencies are used in this study. They are bilateral exchange rates between the United States (USA) and Australia (AUS), Austria (AUT), Belgium (BEL), Canada (CAN), Denmark (DEN), Finland (FIN), France (FRA), Germany (GER), Greece (GRE), Ireland (IRE), Italy (ITA), Japan (JAP), Netherlands (HOL), Norway (NOR), New Zealand (NZL), Singapore (SNG), South Africa (SAR), Spain (SPA), Sweden (SWE), Switzerland (SWI), and the United Kingdom (GBR).

Table 4.1A shows the IFS data codes for exchange rates. Returns from holding currencies are calculated as changes in continuously compounded rates (R_t) as $R_t = \ln(S_t/S_{t-1})$, where S_t is the bilateral exchange rate expressed as the U.S. dollar price of foreign currency. Excess returns (ER_t) are calculated as returns from holding currencies over the risk-free rate of returns as $ER_t = \left(\ln(S_t/S_{t-1}) - (R_{ft} - R^{*}_{ft})\right)$, where R_{ft} is the U.S. risk-free interest rate and R^{*}_{ft} is the foreign risk-free interest rate. Table 4.1B presents the IFS data codes and descriptions of short-term interest rates used to calculate excess returns in this study.

Section 2: Preliminary Analysis

To identify autocorrelation in each of the series, I apply a variance ratio test originally employed in Lo and MacKinlay (1988).[46] The variance ratio (VR) test can be used to detect first-order (and higher-order) autocorrelations of a series at various time horizons (q). If an exchange rate possesses serially uncorrelated increments (a random walk process), the variance of these random walk increments must be linear in the time interval. For instance, the variance of the q-differences is q times the variance of the first differences.[47] This linearity property of the random walk process would imply that

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[46] The derivation of the variance ratio statistics is shown in Chapter 2 under the Data and Methodology section.

[47] Or, equivalently, the variance of the sum of uncorrelated increments must equal the sum of the variances.

the exchange rate is unpredictable. However, if the exchange rate increments are serially correlated and exhibit trends, trading rules that capture regularities in the series should generate some excess returns (to some extent in the short run). In this section, I provide evidence of serially correlated increments in monthly exchange rates.

Table 4.1A

Data Codes for Exchange Rates Vis-à-vis the US Dollar (Direct Quotes)

Country	Period	Exchange Rate
Australia (AUS)	1974:1-1998:12	193..AH.ZF...
Austria (AUT)	1974:1-1998:12	122..AH.ZF...
Belgium (BEL)	1974:1-1998:12	124..AH.ZF...
Canada (CAN)	1974:1-1998:12	156..AH.ZF...
Denmark (DEN)	1974:1-1998:12	128..AH.ZF...
Finland (FIN)	1974:1-1998:12	172..AH.ZF...
France (FRA)	1974:1-1998:12	132..AH.ZF...
Germany (GER)	1974:1-1998:12	134..AH.ZF...
Greece (GRE)	1974:1-1998:12	174..AH.ZF...
Ireland (IRE)	1974:1-1998:12	178..AH.ZF...
Italy (ITA)	1974:1-1998:12	136..AH.ZF...
Japan (JAP)	1974:1-1998:12	158..AH.ZF...
Netherlands (HOL)	1974:1-1998:12	138..AH.ZF...
Norway (NOR)	1974:1-1998:12	142..AH.ZF...
New Zealand (NZL)	1974:1-1998:12	196..AH.ZF...
Singapore (SNG)	1974:1-1998:12	576..AH.ZF...
South Africa (SAR)	1974:1-1998:12	199..AH.ZF...
Spain (SPA)	1974:1-1998:12	184..AH.ZF...
Sweden (SWE)	1974:1-1998:12	144..AH.ZF...
Switzerland (SWI)	1974:1-1998:12	146..AH.ZF...
United Kingdom (GBR)	1974:1-1998:12	112..AH.ZF...

Table 4.1B

Data Codes and Descriptions for Short-Term Interest Rates

Country	Period	Code	Description
Australia (AUS)	1974:1 – 1998:12	19360C..ZF...	13 Weeks' treasury bills
Austria (AUT)	1974:1 – 1998:12	12260B..ZF...	Money market rate
Belgium (BEL)	1974:1 – 1998:12	12460C..ZF...	Treasury paper
Canada (CAN)	1974:1 – 1998:12	15660C..ZF...	Treasury bill rate
Denmark (DEN)	1974:1 – 1998:12	12860B..ZF...	Call money rate
Finland (FIN)	1974:1 – 1977:12	17260...ZF...	Central bank rate
	1978:1 – 1998:12	17260B..ZF...	Average cost of CB debt
France (FRA)	1974:1 – 1998:12	13260B..ZF...	Call money rate
Germany (GER)	1974:1 – 1998:12	13460B..ZF...	Call money rate
Greece (GRE)	1974:1 – 1985:5	17460L..ZF...	CM BK 3-12 mo. deposit
	1985:6 – 1998:12	17460C..ZF...	Treasury bill rate
Ireland (IRE)	1974:1 – 1998:12	17860C..ZF...	Exchequer bills
Italy (ITA)	1974:1 – 1998:12	13660B..ZF...	Money market rate
Japan (JAP)	1974:1 – 1998:12	15860B..ZF...	Call money rate
Netherlands (HOL)	1974:1 – 1998:12	13860B..ZF...	Call money rate
Norway (NOR)	1974:1 – 1998:12	14260B..ZF...	Call money rate
New Zealand (NZL)	1974:1 – 1977:12	19660...ZF...	Discount rate
	1978:1 – 1998:12	19660C..ZF...	New issue 3-mo treasury bills
Singapore (SNG)	1974:1 – 1998:12	57660B..ZF...	3-month Interbank rate
South Africa (SAR)	1974:1 – 1998:12	19960C..ZF...	Treasury bill rate
Spain (SPA)	1974:1 – 1998:12	18460B..ZF...	Call money rate
Sweden (SWE)	1974:1 – 1998:12	14460C..ZF...	3 months treasury disc. Notes
Switzerland (SWI)	1974:1 – 1975:8	14660...ZF...	Discount rate
	1975:9 – 1998:12	14660B..ZF...	Money market rate
United Kingdom (GBR)	1974:1 – 1998:12	11260C..ZF...	Treasury bill rate
United States (USA)	1974:1 – 1998:12	11160C..ZF...	Treasury bill rate

Table 4.2 reports, for each currency, the estimated variance ratios VR(q) in the first row followed by the estimated homoscedastic Z1(q) statistics in the second row, and the estimated heteroscedasticity-consistent Z2(q) statistics in the third row.[48] The results show that the random walk null hypothesis of serially uncorrelated increments is

rejected at the 5 percent level for all currencies up to, in general, q=24 months.[49] Rejection of the null is not due to time-varying variances since the $Z2(q)$ statistics are heteroscedasticity-consistent.

The estimated variance ratios are larger than one for all cases. For example, the average variance ratio with q=2 months for the 21 currencies is 1.312.[50] The VR(2) is approximately equal to 1 plus the first-order autocorrelation coefficient of monthly currency returns (Lo and MacKinlay (1988)). The average VR of 1.312 implies the average first-order autocorrelation of approximately 0.31. In terms of regression analysis, the square of the first-order autocorrelation is simply the R^2 of a regression of a variable on a constant and its first lag. In the economic sense, the average VR of 1.312 implies that 9.73% of the variation in the monthly currency return may be predicted by using the preceding month's return. Therefore, significant positive first-order autocorrelation suggests a certain degree of predictability of exchange rate movements. In the next section, I propose a relative strength trading strategy to obtain speculative returns from currency trading due to this positive serial correlation of changes in the exchange rates.

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[48] Lo and MacKinlay (1988) demonstrate that both test statistics are asymptotically standard normal. Statistical inference may be made using conventional critical values.

[49] The rejections of the null for the AUS, SNG, and SAR currencies occur only up to q=6, 4, and 8 months, respectively.

[50] Note that the VR statistics are based on nominal currency returns. Similar results would obtain with excess returns if the volatility of monthly currency returns is greater than that of interest rate differentials. During the sample period studied, though the differentials are not constant, their monthly variability magnitudes are smaller than those of exchange rate changes.

Table 4.2

Estimates of Variance Ratios and Z-Statistics for Monthly Exchange Rate Changes

q =	2	4	6	8	10	12	18	24
AUS	1.259	1.362	1.259	1.206	1.248	1.285	1.251	1.216
Z1(q)	(4.48)	(3.34)	(1.81)	(1.20)	(1.27)	(1.31)	(0.92)	(0.68)
Z2(q)	(3.34)	(3.69)	(2.29)	(1.64)	(1.80)	(1.92)	(1.40)	(1.07)
AUT	1.305	1.527	1.592	1.642	1.712	1.801	1.951	1.917
Z1(q)	(5.27)	(4.87)	(4.14)	(3.75)	(3.65)	(3.70)	(3.50)	(2.89)
Z2(q)	(5.21)	(6.47)	(5.90)	(5.54)	(5.46)	(5.60)	(5.38)	(4.50)
BEL	1.326	1.606	1.729	1.817	1.932	2.070	2.355	2.475
Z1(q)	(5.63)	(5.60)	(5.10)	(4.78)	(4.78)	(4.93)	(4.99)	(4.65)
Z2(q)	(5.46)	(7.38)	(7.05)	(6.96)	(7.11)	(7.41)	(7.60)	(7.19)
CAN	1.154	1.238	1.264	1.273	1.361	1.517	1.692	1.849
Z1(q)	(2.66)	(2.20)	(1.85)	(1.59)	(1.85)	(2.38)	(2.55)	(2.68)
Z2(q)	(2.47)	(2.72)	(2.54)	(2.31)	(2.77)	(3.65)	(4.02)	(4.29)
DEN	1.309	1.568	1.663	1.735	1.824	1.933	2.132	2.182
Z1(q)	(5.35)	(5.25)	(4.64)	(4.30)	(4.22)	(4.31)	(4.17)	(3.73)
Z2(q)	(5.19)	(6.94)	(6.50)	(6.27)	(6.29)	(6.48)	(6.38)	(5.77)
FIN	1.307	1.492	1.595	1.669	1.743	1.845	1.998	2.071
Z1(q)	(5.31)	(4.55)	(4.16)	(3.91)	(3.81)	(3.90)	(3.67)	(3.38)
Z2(q)	(4.30)	(4.72)	(4.74)	(4.67)	(4.61)	(4.94)	(5.03)	(4.94)
FRA	1.288	1.551	1.725	1.851	1.963	2.079	2.297	2.357
Z1(q)	(4.98)	(5.10)	(5.07)	(4.98)	(4.93)	(4.98)	(4.78)	(4.28)
Z2(q)	(4.81)	(6.67)	(6.91)	(7.02)	(7.19)	(7.26)	(7.13)	(6.47)
GER	1.308	1.517	1.581	1.636	1.709	1.805	1.995	1.980
Z1(q)	(5.33)	(4.78)	(4.07)	(3.72)	(3.63)	(3.71)	(3.67)	(3.09)
Z2(q)	(5.28)	(6.35)	(5.78)	(5.49)	(5.44)	(5.63)	(5.65)	(4.83)
GRE	1.260	1.495	1.500	1.477	1.491	1.555	1.809	1.940
Z1(q)	(4.49)	(4.57)	(3.49)	(2.79)	(2.51)	(2.56)	(2.98)	(2.97)
Z2(q)	(3.84)0	(5.80)	(4.92)	(4.13)	(3.85)	(3.99)	(4.28)	(4.42)

Table 4.2 (Continued)

q =	2	4	6	8	10	12	18	24
IRE	1.312	1.575	1.710	1.799	1.884	1.983	2.139	2.117
Z1(q)	(5.40)	(5.32)	(4.96)	(4.67)	(4.53)	(4.53)	(4.19)	(3.53)
Z2(q)	(5.52)	(7.11)	(6.66)	(6.54)	(6.50)	(6.62)	(6.17)	(5.33)
ITA	1.370	1.670	1.820	1.916	1.999	2.111	2.324	2.390
Z1(q)	(6.40)	(6.20)	(5.74)	(5.35)	(5.12)	(5.13)	(4.88)	(4.39)
Z2(q)	(4.91)	(6.69)	(6.78)	(6.81)	(6.86)	(7.03)	(7.00)	(6.52)
JAP	1.329	1.537	1.610	1.603	1.655	1.714	1.809	1.736
Z1(q)	(5.68)	(4.96)	(4.27)	(3.53)	(3.35)	(3.30)	(2.98)	(2.32)
Z2(q)	(4.56)	(6.15)	(5.88)	(4.87)	(4.72)	(4.69)	(4.50)	(3.65)
HOL	1.322	1.571	1.661	1.722	1.794	1.890	2.060	2.044
Z1(q)	(5.56)	(5.28)	(4.62)	(4.22)	(4.07)	(4.11)	(3.90)	(3.29)
Z2(q)	(5.48)	(6.96)	(6.48)	(6.15)	(6.00)	(6.16)	(5.94)	(5.08)
NOR	1.339	1.554	1.564	1.547	1.551	1.565	1.465	1.425
Z1(q)	(5.86)	(5.12)	(3.95)	(3.20)	(2.82)	(2.61)	(1.71)	(1.34)
Z2(q)	(5.18)	(6.17)	(5.20)	(4.42)	(4.05)	(3.83)	(2.57)	(2.06)
NZL	1.342	1.588	1.664	1.750	1.874	1.981	1.980	1.951
Z1(q)	(5.92)	(5.44)	(4.64)	(4.39)	(4.48)	(4.53)	(3.61)	(3.00)
Z2(q)	(3.21)	(4.65)	(4.82)	(4.93)	(5.33)	(5.57)	(4.87)	(3.85)
SNG	1.270	1.334	1.284	1.254	1.254	1.254	1.242	1.183
Z1(q)	(4.68)	(3.09)	(1.99)	(1.49)	(1.30)	(1.17)	(0.89)	(0.58)
Z2(q)	(2.55)	(2.47)	(1.86)	(1.47)	(1.32)	(1.30)	(0.99)	(0.70)
SAR	1.323	1.586	1.492	1.353	1.349	1.419	1.546	1.386
Z1(q)	(5.59)	(5.42)	(3.44)	(2.07)	(1.79)	(1.93)	(2.01)	(1.22)
Z2(q)	(3.22)	(5.21)	(3.44)	(2.06)	(1.70)	(1.77)	(1.94)	(1.21)
SPA	1.353	1.632	1.785	1.959	2.143	2.296	2.554	2.723
Z1(q)	(6.11)	(5.84)	(5.49)	(5.60)	(5.85)	(5.98)	(5.72)	(5.44)
Z2(q)	(4.77)	(6.83)	(7.33)	(8.01)	(8.74)	(9.16)	(9.04)	(8.62)

Table 4.2 (Continued)

q =	2	4	6	8	10	12	18	24
SWE	1.405	1.724	1.849	1.901	2.002	2.112	2.176	2.296
Z1(q)	(7.01)	(6.70)	(5.94)	(5.27)	(5.13)	(5.13)	(4.33)	(4.09)
Z2(q)	(4.40)	(6.55)	(6.82)	(6.38)	(6.48)	(6.78)	(6.06)	(6.06)
SWI	1.321	1.532	1.577	1.609	1.655	1.707	1.773	1.730
Z1(q)	(5.56)	(4.92)	(4.04)	(3.56)	(3.35)	(3.26)	(2.85)	(2.30)
Z2(q)	(5.55)	(6.40)	(5.55)	(5.21)	(5.06)	(4.98)	(4.40)	(3.63)
GBR	1.354	1.553	1.626	1.649	1.686	1.728	1.740	1.800
Z1(q)	(6.12)	(5.11)	(4.38)	(3.79)	(3.51)	(3.36)	(2.73)	(2.53)
Z2(q)	(4.68)	(5.76)	(5.10)	(4.65)	(4.49)	(4.36)	(3.77)	(3.66)

Section 3: Trading Strategies

When exchange rates exhibit long swings due to, perhaps, either overreaction or underreaction to information about fundamentals, trading strategies that buy and sell currencies based on their past movements will be profitable. This study examines the profitability of a number of relative strength trading rules in the FX markets. The strategies are constructed similar to those in Jegadeesh and Titman (1993) and Rouwenhorst (1998). The strategies select currencies based on their past J-month movements (J equals 3, 6, 9, or 12) and consider holding periods for K subsequent months (K equals 3, 6, 9, or 12). Each strategy is referred to as a J-month/K-month strategy. The strategies include overlapping holding periods to increase the power of the statistical tests. In any given month *t*, the strategies hold portfolios of currencies that are selected in the current month as well as in the previous K-1 months. At the beginning of each month, all currencies are classified whether they have appreciated or depreciated against the U.S. dollar based on the past J-month movements. Then, two equally weighted portfolios are formed. In each month *t*, the strategy takes a long position in a portfolio of appreciating currencies (Long portfolio) and a short position in a portfolio of depreciating currencies (Short portfolio) and hold this position for K subsequent months.[51] For each strategy, both Long and Short portfolios are then combined into an equally weighted composite portfolio. The rate of return of the equally weighted composite portfolio (R_p) is

$$R_p = w_L R_L + w_S R_S, \quad (4.1)$$

where w_L and w_S are the weights of the Long and Short portfolios, respectively and $w_L + w_S = 1$. Returns R_L and R_S are those from the Long and Short portfolios, respectively.

The strategy also closes out the position initiated in month *t*-K for any month *t*. Each month the weights on 1/K of the currencies in the entire portfolio are revised and the rest from the previous K-1 months are carried over. For example, each month the J=3/K=3 strategy liquidates the position initiated in month *t*-3 and invests in the Long and Short portfolios evaluated at time *t*. The strategy carries over portfolios formed in months *t*-2 and *t*-1. In addition, to avoid the continuation effect from bid-ask bounce, the strategies skip a month between the portfolio formation period and the holding period (Jegadeesh and Titman (1993) and Rouwenhorst (1998)).

Section 4: Returns from Relative Strength Strategies

Table 4.3A presents the average monthly returns on the Long, Short, and composite equally weighted portfolios formed at the end of the performance evaluation

[51] This study assumes that investors do not face short sale restrictions. Short selling is often restricted especially for portfolio managers dealing with hedging. In addition, a currency is not included in a speculating portfolio if it is neither appreciating nor depreciating.

period.[52] The returns of all composite portfolios are positive and statistically significant at the 5 percent level. In general, average returns tend to increase for longer holding periods up to 9 months and slightly fall in the 12-month holding period. Sources of these positive returns are primarily from the Short portfolios. None of the returns from the long position in portfolios of appreciating currencies are statistically significant.

Table 4.3B reports the average monthly returns in which there is a 1-month delay between the portfolio formation period and the holding period. Bid-ask pressure may cause measurement error in the returns. For example, Blume and Stambaugh (1983) suggest that bid-ask bounce may overstate long-term profitability calculated from averaging short-term returns over time. As a result, delaying the portfolio formation slightly lowers the average returns (Table 4.3B). The decreased average returns are mainly due to lower returns from the Short portfolios. The returns of the Long portfolios are again not statistically significant.

The most successful strategy is the J=9/K=9 strategy. The average return of the composite portfolio is 1.86% per month, or 22.32% per year, when there is no time lag between the formation and holding periods. When the portfolio formation is delayed (Table 4.3B) the average returns from the J=9/K=9 strategy reduces to 1.55% per month, or 18.60% per year. In the next section, I calculate returns from holding portfolios of currencies in excess of rate of returns from interest rate differentials.

[52] The effective sample period is from January 1976 through December 1998. The J=12/K=12 strategy requires a 12 month holding period which is based on prior 12 month exchange rate movements. Two years are lost due to performance ranking of this J=12/K=12 strategy.

Table 4.3A

Average Monthly Returns from Relative Strength Strategies

Ranking Period (J)	Portfolio	Holding Period (K)			
		3	6	9	12
3	Long	-0.0024	-0.0060	-0.0082	-0.0011
		(0.97)	(1.57)	(1.67)	(1.85)
3	Short	0.0060	0.0109	0.0148	0.0183
		(2.63)	(3.06)	(3.26)	3.27
3	Long+Short	0.0034	0.0060	0.0096	0.0111
		(2.23)	(2.45)	(3.01)	(2.75)
6	Long	-0.0011	-0.0041	-0.0075	-0.0091
		(0.42)	(1.05)	(1.49)	(1.49)
6	Short	0.0055	0.0100	0.0150	0.0187
		(2.36)	(2.79)	(3.26)	(3.27)
6	Long+Short	0.0034	0.0074	0.0111	0.0105
		(2.11)	(2.96)	(3.51)	(2.71)
9	Long	-0.0024	-0.0053	-0.0082	-0.0093
		(0.96)	(1.36)	(1.64)	(1.54)
9	Short	0.0047	0.0088	0.0127	0.0163
		(2.03)	(2.45)	(2.69)	(2.79)
9	Long+Short	0.0081	0.0146	0.0186	0.0161
		(5.01)	(6.32)	(6.23)	(4.26)
12	Long	-0.0036	-0.0063	-0.0083	-0.0090
		(1.42)	(1.59)	(1.66)	(1.48)
12	Short	0.0054	0.0100	0.0124	0.0153
		(2.36)	(2.79)	(2.69)	(2.68)
12	Long+Short	0.0072	0.0123	0.0169	0.0165
		(4.36)	(4.93)	(5.52)	(4.27)

Parentheses contain *t*-statistics.

Table 4.3B

Average Monthly Returns from Relative Strength Strategies with One Month Lag

Ranking Period (J)	Portfolio	Holding Period (K) 3	6	9	12
3	Long	-0.0034	-0.0066	-0.0098	-0.0130
		(1.38)	(1.72)	(1.95)	(2.14)
3	Short	0.0055	0.0104	0.0143	0.0178
		(2.36)	(2.89)	(3.13)	(3.15)
3	Long+Short	0.0025	0.0053	0.0088	0.0095
		(1.59)	(2.03)	(2.63)	(2.27)
6	Long	-0.0022	-0.0056	-0.0084	-0.0098
		(0.86)	(1.40)	(1.67)	(1.60)
6	Short	0.0051	0.0099	0.0151	0.0180
		(2.21)	(2.76)	(3.26)	(3.14)
6	Long+Short	0.0025	0.0071	0.0094	0.0084
		(1.49)	(2.81)	(2.87)	(2.13)
9	Long	-0.0028	-0.0058	-0.0088	-0.0097
		(1.11)	(1.49)	(1.78)	(1.62)
9	Short	0.0045	0.0087	0.0129	0.0158
		(1.98)	(2.43)	(2.71)	(2.70)
9	Long+Short	0.0073	0.0132	0.0155	0.0133
		(4.61)	(5.81)	(5.13)	(3.47)
12	Long	-0.0037	-0.0061	-0.0082	-0.0087
		(1.45)	(1.57)	(1.65)	(1.45)
12	Short	-0.0061	0.0092	0.0121	0.0144
		(1.57)	(2.57)	(2.63)	(2.54)
12	Long+Short	0.0057	0.0113	0.0141	0.0138
		(3.41)	(4.63)	(4.60)	(3.63)

Parentheses contain *t*-statistics.

Section 5: Excess Returns

To calculate excess returns, raw returns must be adjusted for interest rate differentials. This study assumes that trading strategies are implemented by a speculator whose wealth is in U.S. dollars.[53] The speculator in this study is equipped with initial wealth that provides him a line of credit to trade foreign currencies on an exchange (or with a commercial bank). When a speculator takes a long position in portfolios of appreciating currencies, he borrows the U.S. dollars and converts the proceeds into foreign currencies at the spot exchange rate. He then deposits the funds and earns interest denominated in the currencies he is holding. By analogy, the speculator borrows foreign currencies and converts them into the U.S. dollars when he goes short on portfolios of depreciating currencies. The speculator earns the U.S. risk-free interest rates and pays foreign-currency-denominated interests on the borrowed funds. The excess return (ER_t) of currency speculation over the risk-free rate of interest is thus

$$ER_t = d_t\left(\ln\left(S_t / S_{t-1}\right) - \left(R_{ft} - R^*_{ft}\right)\right), \tag{4.2}$$

where R_{ft} is the U.S. risk-free interest rate and R^*_{ft} is the foreign risk-free interest rate. The dummy variable d_t is equal to +1 for a long position and −1 for a short position. Under the joint null hypothesis of market efficiency and no currency risk premium, the excess return in equation (2) should not be significantly different from zero.

Table 4.4A presents the average monthly excess returns when portfolios are formed at the end of the evaluation period. Average excess returns are negative for all the Short portfolios and only 6 cases are statistically significant at the 5 percent level.

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[53] The trading strategies are the same with a foreign investor whose wealth is denominated in foreign currencies.

With the exception of two strategies, average excess returns are positive for the Long portfolios and only 4 strategies provide statistically significant positive returns. The excess returns of all composite portfolios, however, are positive and statistically significant at the 5 percent level. The composite portfolios average the returns from both long and short positions and, perhaps for each month *t*, put more weights on the portfolio that provides higher returns.

The interest differential is the culprit behind the contrary results of the Long and Short portfolios between Tables 4.3A and 4.4A. During the sample period, the U.S. risk-free interest rate is lower than the average interest rate of all 21 foreign countries (Figure 2).[54] When the speculator takes a long position, he not only earns interests from foreign deposits (due to more interest income than interest payment) but also, for some periods, profits from currency appreciation.[55]

The interest rate parity hypothesis suggests that a country whose currency has depreciated will offer higher interest rates to attract the home currency into the country. Relatively higher interest rates should lead to immediate home currency appreciation. However, if only one part of this appreciation occurs instantaneously and the other part responds with lags, continuing appreciation of the currency in subsequent periods following an increase in interest rates might be expected (Froot and Thaler (1990)). An American speculator may expect this situation and thus, after witnessing an initial appreciation, will go long on that currency in anticipation of a certain degree of continuation. This strategy will produce returns over the risk-free rate of return if the

[54] The exception is during the 1979-1981 period and in 1997.
[55] Bilson (1981) also suggests a speculative rule of buying the currency whose interest rate is relatively high.

currency continues to appreciate and on the average the foreign interest rate is higher than the U.S. rate.[56]

By arbitrage, these abnormal returns will not persist, however. Eventually, the foreign country will lower its interest rate or the U.S. interest rate will increase. This arbitrage argument is evident in Table 4.4A. The excess returns on the Long portfolios become statistically indistinguishably different from zero for holding periods longer than 3 months.[57] The continuation effect only persists in the short run.[58]

The most successful strategy is the J=9/K=9 strategy. It provides the average excess returns of 2.04% per month, or 24.48% per year. Table 4.4B reports the average excess returns in which the strategies skip a month between the portfolio formation and holding periods. In general, the results are similar to those in Table 4.4A. Only the magnitude of the returns is smaller.

In sum, significant positive excess returns in this section imply the rejection of the joint null hypothesis of market efficiency and no currency risk premium. In the next section, I examine whether theses excess returns are the result of market inefficiency or compensation for risk.

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[56] The same analogy applies to an analysis of a portfolio of appreciating currencies (Long portfolios).
[57] The exception is the J=12/K=3 strategy. The excess returns from the Long portfolio of this strategy is not statistically significant even in the short-run 3-month holding period.
[58] The same inference applies to the Short portfolios.

Table 4.4A

Average Monthly Excess Returns

Ranking Period (J)	Portfolio	Holding Period (K)			
		3	6	9	12
3	Long	0.0121	0.0087	0.0070	0.0030
		(3.60)	(1.90)	(1.26)	(0.46)
3	Short	-0.0128	-0.0083	-0.0045	-0.0016
		(3.53)	(1.75)	(0.80)	(0.24)
3	Long+Short	0.0057	0.0083	0.0121	0.0135
		(2.37)	(2.67)	(3.22)	(3.02)
6	Long	0.0124	0.0095	0.0064	0.0043
		(3.73)	(2.03)	(1.30)	(0.65)
6	Short	-0.0116	-0.0075	-0.0029	-0.0001
		(3.15)	(1.56)	(0.51)	(0.02)
6	Long+Short	0.0063	0.0101	0.0138	0.0128
		(2.59)	(3.18)	(3.64)	(2.91)
9	Long	0.0078	0.0046	0.0017	0.0006
		(2.09)	(0.92)	(0.29)	(0.09)
9	Short	-0.0154	-0.0121	-0.0087	-0.0064
		(4.16)	(2.46)	(1.43)	(0.91)
9	Long+Short	0.0107	0.0166	0.0204	0.0172
		(4.00)	(5.13)	(5.47)	(4.01)
12	Long	0.0050	0.0021	-0.0001	-0.0008
		(1.36)	(0.44)	(0.02)	(0.12)
12	Short	-0.0146	-0.0111	-0.0098	-0.0083
		(3.94)	(2.22)	(1.62)	(1.20)
12	Long+Short	0.0104	0.0149	0.0188	0.0177
		(4.02)	(4.69)	(5.19)	(4.18)

Parentheses contain *t*-statistics.

Table 4.4B

Average Monthly Excess Returns with One Month Lag

Ranking Period (J)	Portfolio	Holding Period (K)			
		3	6	9	12
3	Long	0.0103	0.0072	0.0046	-0.0004
		(3.06)	(1.58)	(0.81)	(0.57)
3	Short	-0.0141	-0.0098	-0.0060	-0.0032
		(3.83)	(2.05)	(1.06)	(0.47)
3	Long+Short	0.0041	0.0067	0.0104	0.0109
		(1.67)	(2.07)	(2.66)	(2.38)
6	Long	0.0107	0.0075	0.0047	0.0031
		(3.09)	(1.56)	(0.81)	(0.46)
6	Short	-0.0121	-0.0079	-0.0030	-0.0011
		(3.32)	(1.67)	(0.53)	(0.17)
6	Long+Short	0.0049	0.0092	0.0116	0.0100
		(1.88)	(2.76)	(2.89)	(2.20)
9	Long	0.0066	0.0034	0.0003	-0.0006
		(1.76)	(0.67)	(0.05)	(0.08)
9	Short	-0.0158	-0.0123	-0.0087	-0.0071
		(4.23)	(2.46)	(1.43)	(1.01)
9	Long+Short	0.0097	0.0150	0.0170	0.0140
		(3.61)	(4.69)	(4.57)	(3.25)
12	Long	0.0046	0.0020	-0.0003	-0.0008
		(1.28)	(0.42)	(0.05)	(0.12)
12	Short	-0.0145	-0.0116	-0.0010	-0.0090
		(3.88)	(2.31)	(1.67)	(1.31)
12	Long+Short	0.0087	0.0137	0.0157	0.0147
		(3.34)	(4.36)	(4.35)	(3.48)

Parentheses contain *t*-statistics.

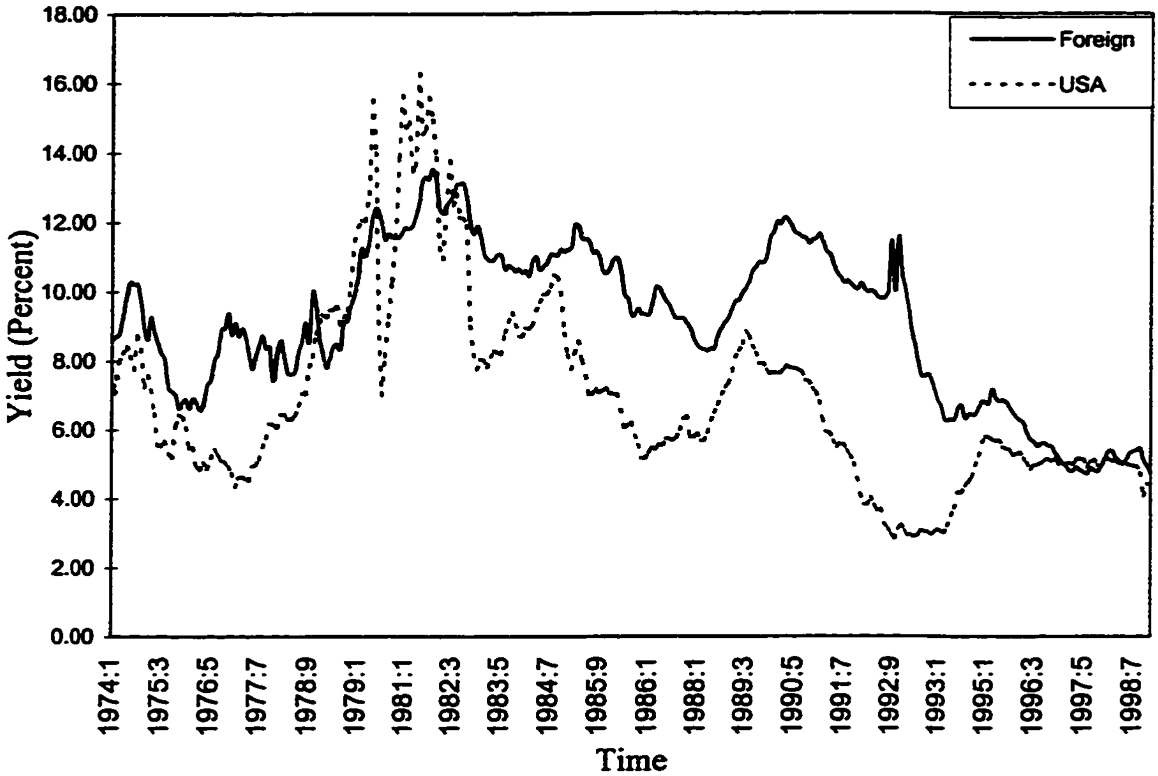

Figure 2: Short-Term Interest Rates

Section 6: Risk-Adjusted Excess Returns

An equilibrium economic paradigm in which exchange rates are rationally determined must be identified to address economic excess returns. The positive excess returns may be the result of chance, market inefficiency, or compensation for a risk premium. In the monetary model, interest differential offsets the exchange rate change since domestic and foreign bonds are perfect substitutes. Abnormal returns from any trading strategy in excess of a buy-and-hold strategy would suggest market inefficiency. In the portfolio balance model, however, domestic and foreign bonds are imperfect substitutes, implying the presence of risk premium to compensate investors to hold currencies. In other words, expected changes in exchange rates do not have to be equal the interest differential if there is a risk premium. Some excess returns from trading strategies would be consistent with the market efficiency if they are compensated for risk (Levich and Thomas (1993)).

This study incorporates a constant risk premium when measuring profitability of relative strength strategies. I follow Sweeney (1986) and derive risk-adjusted excess returns in terms of a single-period Sharp-Lintner capital asset pricing model (CAPM). By assuming that the "market" index (R_M) and the domestic and foreign risk-free rates are known, the CAPM implies[59]

$$E(R) + R_f^* - R_f = \beta_f\left(E(R_M) - R_f\right), \tag{4.3}$$

where $E(R)$ is the expected percentage appreciation of the foreign currency and $\beta_f = \mathrm{cov}(R, R_M)/\mathrm{var}(R_M)$. The term $\beta_f\left(E(R_M) - R_f\right)$ is the risk premium and it is

[59] Since this is a one-period analysis, the subscript t is dropped without loss of generality.

explicitly assumed to be constant under the CAPM. If there is no risk premium (i.e., $\beta_f = 0$), expected currency appreciation is equal to the interest rate differential: $\left(E(R) + R_f^* - R_f = 0\right)$. Interest differential offsets the exchange rate changes as in the monetary model. However, expected changes in exchange rates do not have to be equal to the interest differential if there is a risk premium: $\left(E(R) + R_f^* - R_f \neq 0 \text{ if } \beta_f \neq 0\right)$. The equivalent "market model" of equation (4.3) is

$$E(R) + R_f^* - R_f = \alpha + \beta_f\left(R_M - R_f\right) + e, \tag{4.4}$$

where by assumption $\text{cov}\left(R_M, e\right) = 0, E(e) = 0$, and $\text{cov}\left(e_t, e_{t-j}\right) = 0$ for $j \neq 0$.[60]

Following Sweeney (1986), I assume that expected premium on the market $\left(E\left(R_M\right) - R_f\right)$ and β_f are constant. Changes in expected appreciation must be equal to changes in the interest differential: $\left(\Delta E(R) = \Delta\left(R_f - R_f^*\right)\right)$. Both *E(R)* and $\left(R_f - R_f^*\right)$ may vary, but their differences must remain equal to the constant risk premium. Thus, the risk premium (*RP*) is simply the returns from a buy-and-hold strategy (R_{BH})

$$RP = R_{BH} = E(R) + R_f^* - R_f, \tag{4.5}$$

which is the uncovered interest rate parity. Each month, the strategy holds both long and short positions simultaneously. In the notations of equation (4.1), R_{BH} may be described as

$$R_{BH} = \left(w_L + w_S\right)ER_L. \tag{4.6}$$

The risk-adjusted excess return on a composite portfolio $\left(ER_p^r\right)$ is thus

$$ER_p^r = ER_p - R_{BH}, or$$
$$ER_p^r = w_S(ER_S - ER_L), \quad (4.7)$$

where ER_S, ER_L and ER_p are the excess returns calculated as in equation (4.2) from the Short, Long, and composite portfolios. The superscript r denotes risk-adjusted.

Table 4.5 reports the risk-adjusted excess returns of the 32 relative strength strategies. Panel A shows the returns when portfolios are formed at the end of the ranking period. Panel B exhibits the returns when there is a 1-month lag between the ranking and holding periods. Twenty-one strategies provide the risk-adjusted excess returns that are not statistically significant different from zero. Eleven strategies give statistically significant negative returns. With constant currency risk premia, the relative strength strategy can not outperform a simple buy-and-hold strategy. For the 3-month holding period, the risk-adjusted excess returns are even negative. The buy-and-hold strategies provide higher returns! The excess speculative returns found in the previous section may be rewards for the speculative risk. Froot and Thaler (1990) also suggest that the returns from currency speculation may not be very attractive because the risk involved is too high.[61]

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[60] Market efficiency requires that forecasting R_M (market timing) or e (asset selection) may not systematically be implemented (Sweeney (1986)).
[61] The risk-return tradeoff will become even less attractive when transaction costs are considered.

Table 4.5

Risk-Adjusted Excess Returns

Ranking Period (J)	Holding Period (K)			
	3	6	9	12
Panel A				
3	-0.0166	-0.0098	-0.0033	0.0018
	(4.34)	(1.98)	(0.56)	(0.26)
6	-0.0182	-0.0107	-0.0021	-0.0004
	(4.58)	(2.04)	(0.32)	(0.05)
9	-0.0121	-0.0035	0.0043	0.0044
	(2.89)	(0.61)	(0.59)	(0.50)
12	-0.0109	-0.0027	0.0036	0.0050
	(2.56)	(0.46)	(0.49)	(0.59)
Panel B				
3	-0.0178	-0.0112	-0.0039	0.0007
	(4.33)	(2.18)	(0.63)	(0.09)
6	-0.0187	-0.0103	-0.0032	-0.0029
	(4.55)	(1.89)	(0.46)	(0.34)
9	-0.0128	-0.0043	0.0023	0.0017
	(3.00)	(0.76)	(0.32)	(0.20)
12	-0.0122	-0.0042	0.0009	0.0017
	(2.79)	(0.72)	(0.12)	(0.20)

Parentheses contain *t*-statistics.

The portfolio balance model of exchange rates implies that investors holding foreign currencies require a risk premium to compensate them for the uncertainty due to exchange rate movements. Some excess returns from trading strategies would be consistent with an equilibrium condition of market efficiency. Therefore, the results in this section suggest that the joint hypothesis of market efficiency and constant currency risk premium can not be rejected.

Section 7: Conclusion

This study documents currency returns from relative strength trading strategies over the 1974 to 1998 period. The strategies generate significant abnormal returns even after adjustment for interest rate differentials. For example, the J=9/K=9 strategy that selects currencies based on their past 9-month changes and holds them for 9 months provides the average excess returns of 2.04% per month. However, risk-adjusted excess returns are not statistically significant different from zero under the assumption of constant currency risk premium and stationary returns variance. The relative strength strategy can not outperform a buy-and-hold strategy. The results in this study are therefore consistent with the joint hypothesis of market efficiency and a constant currency risk premium.

The evidence of short-term return continuation under the market efficiency world with no risk premium may be viewed in the context of investor psychology. The market may underreact to information about short-term movements of fundamentals. Investors may mistakenly think that changes in fundamentals are temporary. However, if in fact fundamentals changes are permanent, an initial partial response of the investors will be followed by subsequent responses in the same direction. As a consequence, the delayed response (underreaction) to changes in the fundamentals will cause exchange rates to exhibit short-run price momentum. The positive serial dependency in exchange rates will enable a trading strategy that buys as the currency value rises and sells as the currency value falls to be profitable to some extent in the short run.

However, with the presence of risk premium, short-run excess returns may be rewards for taking some risks. Some excess returns from trading strategies would be consistent with the Efficient Markets Hypothesis. I use a simple concept of a speculative activity to illustrate. Any regularities in exchange rate changes offer profitable opportunities to speculators. The speculators will enter the market to exploit these speculative profit opportunities. Due to, perhaps, heterogeneous expectations, the speculators may in the process cause exchange rates to swing. The speculative activities may increase the variability of returns. The payoffs from trading strategies over those of a simple buy-and-hold strategy will become less favorable due to increased speculative risk. As evident in this study, the excess returns from trading strategies can be explained by risk. Or, equivalently, the risk-return tradeoff under the assumption of market efficiency and a constant risk premium provides an explanation of returns continuation found in this study.

CHAPTER 5

CONCLUSION

This dissertation is a collection of three research essays examining (1) time-series behavior of monthly real exchange rates, (2) statistical properties of daily spot rates, and (3) relative strength trading strategies and foreign exchange market efficiency. This dissertation has provided to the body of knowledge increased information about exchange rate behavior. First, there is a significant mean-reverting component in each of the monthly real exchange rates studied. Second, the distributions of spot rate changes vary over time due to non-stationary variance of the fundamental component. And, with a constant risk premium, the foreign exchange market seems to be efficient (at least in its weak form).

Chapter 2 shows that real exchange rates during the 1974-1997 period do not follow a pure random walk process. The analysis of autocorrelations and variance ratio tests suggests that changes in monthly real exchange rates exhibit significant positive first-order autocorrelations at lower lags. Using the Beveridge-Nelson decomposition technique, each of the real exchange rates may be decomposed into a permanent and a transitory component and thus represented by the sum of a random walk and a mean-reverting process. The presence of the transitory component in real exchange rates is highly persistent and may be responsible for long swings of real exchange rates away from a long-run equilibrium path.

Chapter 3 shows that percentage changes in daily spot rates during the period January 1974 through August 1998 are not normally distributed. Their distributions are more peaked and fat-tailed than a normal distribution and vary over time due to changes in variance of the fundamental component. The results suggest that (1) exchange rates may be drawn from a normal distribution with non-stationary variance, (2) exchange rates may contain discrete jumps possibly due to market overreaction or government intervention, or (3) exchange rates follow both (1) and (2) processes. I propose an AR(1)-GARCH(1,1) model to describe statistical properties of daily spot rates. The model is able to capture non-stationary variances for all currencies studied.

Chapter 4 documents currency returns from relative strength trading strategies in the foreign exchange market over the 1974 to 1998 period. The strategies generate significant excess returns even after adjustment for interest rate differentials. However, the excess returns vanish after adjustment for a constant currency risk premium. The relative strength strategy can not outperform a simple buy-and-hold strategy. Thus, the results are consistent with the joint hypothesis of market efficiency and a constant risk premium.

This chapter is organized as follows. Section 1 provides economic implications pertaining to the results in this study. Section 2 discusses limitations of the study. Section 3 offers suggestions for future research in international finance.

Section 1: Economic Implications

Understanding the underlying process determining foreign exchange rates should help in creating models that provide satisfactory empirical performance, assessing risk and expected returns of holding foreign currencies, and formulating an exchange rate management policy. The analysis in Chapter 2 suggests that monthly real exchange rates have a mean-reverting characteristic. Empirical exchange rate modeling should properly account for this time-series characteristic. The results in Chapter 3 suggest that conventional asset pricing models used to assess the risk and expected returns should be modified to incorporate leptokurtosis in daily spot rates. Furthermore, policymakers who are concerned with the stability and level of exchange rates should consider both mean-reverting behavior and leptokurtosis in the distribution of exchange rates to obtain more accurate exchange rate forecast and more effective exchange rate management policies.

Chapter 4 shows that risk-adjusted excess returns are not statistically different from zero. The results are in accordance with the joint hypothesis of market efficiency and a constant currency risk premium. From a policy point of view, if the foreign exchange markets are efficient, government intervention may cause fluctuations and distort the level of exchange rates. Large exchange rate fluctuations may cause exchange rates to be more volatile and, perhaps, destabilized. The excess volatility may lead both producers and consumers to make less efficient allocative decisions. Market efficiency suggests that prices should fully reflect information available to market participants and, for each time domain, the market prices should represent the true asset values. Thus, government intervention impacting price movements tends to make the market less efficient.

Section 2: Limitations of the study

This dissertation is subject to certain limitations that may affect the outcomes of the study. Chapter 2 uses the Beveridge-Nelson decomposition technique to decompose real exchange rates into permanent and transitory components. One assumption underlying the Beveridge-Nelson decomposition is that innovations of both permanent and transitory components are perfectly correlated. Shocks to real exchange rates will have both permanent and temporary effects. However, if the innovations of both components are orthogonal, the assumption is violated. Certain shocks will have a permanent effect while the others will have only a transitory effect. The results of mean-reverting behavior of real exchange rates found in the study may no longer hold.

In Chapter 3, I model the logarithm of daily spot rates as the sum of a random walk and an AR(1) process with ARCH errors. In certain aspects, the model is not able to fully explain leptokurtosis in spot rates. The AR(1)-GARCH(1,1) model is based on the fads model of Summers (1986). Different statistical models may better account for the leptokurtosis in the data and provide improved empirical performance.

Chapter 4 uses a relative strength investment strategy to examine foreign exchange market efficiency. The study assumes a constant risk premium derived in the context of the CAPM. However, some studies suggest that exchange rates may contain time-varying risk premia. The results in Chapter 4 merely suggest that the foreign exchange market is efficient if a currency risk premium is constant over time. Some caution should be used when one interprets excess returns from any trading strategies.

Section 3: Suggestions for Future Research

Chapter 2 examines real exchange rate behavior only in a univariate framework. A multivariate analysis of a system of several real exchange rates may provide interesting findings. In addition, the same econometric techniques employed in this study may be used to investigate exchange rate behavior of developing countries. Chapter 3 proposes an AR(1)-GARCH(1,1) model to describe daily spot rates. Different model specifications may be attempted to fit the data. A study of the statistical properties of thinly-traded currencies is also an interesting topic. Chapter 4 uses only a relative strength trading strategy to examine foreign exchange market efficiency. Other investment strategies or testing using different data frequencies may be attempted. It may also be interesting to examine foreign exchange market efficiency under a time-varying risk premium context.

Besides the aforementioned suggestions, future research should attempt to derive theoretical models to explain significant positive autocorrelations at lower lags of both real and nominal exchange rates. Future studies should examine not only macroeconomic models of exchange rates but also trading activities in and microstructure of foreign exchange market *per se*. Analysis of these issues of exchange rate studies should make a significant contribution to the international finance literature.

APPENDIX

A FADS MODEL

This Appendix shows the relationship between the AR(1)-GARCH(1,1) process in equation (3.15) and the permanent and transitory components processes in equations (3.11) and (3.12), respectively. Let first consider equation (3.15).

$$R_t = \mu + \phi R_{t-1} + \varepsilon_t . \qquad \text{(A1)}$$

The AR(1) process as in equation (A1) can also be expressed as the MA(∞) process.[62]

$$R_t = \mu(1-\phi)^{-1} + \varepsilon_t + \phi\varepsilon_{t-1} + \phi^2\varepsilon_{t-1} + \ldots . \qquad \text{(A2)}$$

Using equation (3.7) and based on the process in (A2), changes in the permanent component is

$$S_t^P - S_{t-1}^P = (1 + \phi + \phi^2 + \ldots)\varepsilon_t , \qquad \text{(A3)}$$

which is a random-walk process with the unconditional variance of $(1+\phi+\phi^2+\ldots)^2\varepsilon_t^2$.

The transitory component in equation (3.12) is an AR(1) process or MA(∞) process of the form

$$S_t^T = \rho S_{t-1}^T + \varepsilon_t , \text{ or} \qquad \text{(A4)}$$

$$S_t^T = (\phi + \phi^2 + \phi^3 + \ldots)\varepsilon_t + (\phi^2 + \phi^3 + \ldots)\varepsilon_{t-1} + \ldots , \qquad \text{(A5)}$$

where $\rho = \phi^2 + \phi^3 + \phi^4 + \ldots = \phi^2(1-\phi)^{-1}$.

[62]For simplicity, I assume μ=0 without loss of generality in subsequent equations.

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IMAGE EVALUATION TEST TARGET (QA-3)

150mm

6"

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