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Testing the Expectations Hypothesis on the Term Structure of Volatilities in Foreign Exchange Options

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ABSTRACT

This article tests the expectations hypothesis in the term structure of volatilities in foreign exchange options. In particular, it addresses whether long-dated volatility quotes are consistent with expected future short-dated volatility quotes, assuming rational expectations. For options observed daily from December 1, 1989 to August 31, 1992 on dollar exchange rates against the pound, mark, yen, and Swiss franc, we are unable to reject the expectations hypothesis in the great majority of cases. The current spread between long- and short-dated volatility rates proves to be a significant predictor of the direction of future short-dated rates.

THE STOCHASTIC NATURE OF VOLATILITY has become widely accepted in both the theoretical and empirical literature on options. When constant volatility models such as Black-Scholes are used to price options of different maturities on the same underlying asset, consistency would require that the implied volatility be independent of the options' maturities. Yet, in practice, using the pricing equations generated by these models to derive implied volatilities from observed option prices on the same underlying asset often results in different levels of implied volatility for different maturities. This reflects the market's assessment of the uncertainty *per unit time* over different horizons. Comparing these implied volatilities thus leads to a "term structure" of implied volatilities.

The purpose of this article is to test the "expectations hypothesis" in the "term structure" of volatilities quoted for over-the-counter options on foreign currencies.[1] In other words, we wish to ascertain whether the long (volatility)

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[1] The data used in this study are bid and ask volatility rate quotes for at-the-money-forward over-the-counter options. A trade at the ask, for example, means that the option buyer pays the option seller an option premium equal to the theoretical option value where the ask volatility rate is used as the formula's volatility parameter.

rate is consistent with expected future short rates, based on the linearity of variance with respect to time. For example, if three-month volatility is currently quoted at 14 percent and six-month volatility is currently quoted at 12 percent, will three-month volatility three months from now be quoted at 9.59 percent?[2]

The foreign exchange options used in this study trade in the interbank market with standard maturities of one, two, three, six, and twelve months. Bid and ask (volatility) rates for these options are quoted throughout the trading day in terms of volatilities, which option traders then substitute into the Garman-Kohlhagen (1983) pricing formula for options on foreign currencies.[3] In examining the expectations hypothesis, we also address the related question: Does the current spread between the long (volatility) rate and the short rate help predict future movements in the short rate? Even if the expectations hypothesis does not hold, it is still possible that the current spread provides useful information for the prediction of the future volatility.

Existing empirical literature on foreign exchange options has typically focused on evaluating alternative pricing models, normally comparing Garman-Kohlhagen values against those implied either by other models or by historical data. For example, Melino and Turnbull (1990) find that a stochastic-volatility model better prices foreign currency options than does a constant-volatility Black-Scholes model. Borensztein and Dooley (1987) and Melino and Turnbull (1991), among others, find that when a constant volatility model is used, foreign exchange options are overpriced relative to their theoretical value based on the observed second moment in the time series behavior of the underlying variable.

Unlike papers that compare implied volatility against realized, this article compares volatility quoted on one date versus volatility quoted at a later date. Previous academic work focusing on volatility term structure includes Stein (1989), which documents "overreactions" of long-run options prices to changes in short-run volatility using (approximately) one- and two-month options on the S&P Index, and Xu and Taylor (1994), which describes movements in the term structure of implied volatilities of foreign exchange options traded on the Philadelphia Stock Exchange. Xu and Taylor (1994) examine dollar-pound, dollar-mark, dollar-yen, and dollar-Swiss franc options, and show that the slope of the term structure of these volatilities changed frequently during the 1985 to 1989 period. Furthermore, at any instant in time, the sign of the slope of the term structure tended to be the same across currencies. This article differs from Xu and Taylor (1994) in that we analyze the consistency of the current observed term structure with the behavior of future volatility quotes.

[2] If so, then the 6-month implied variance of $\frac{1}{2}(.12)^2$ is consistent with the successive 3-month implied variances of $\frac{1}{4}(.14)^2 + \frac{1}{4}(.0959)^2$.

[3] To derive the option premium from the model, option traders use these volatility quotes as well as corresponding interbank foreign exchange forward rates and Eurocurrency interest rates (both foreign and domestic) consistent with the time horizon of the option.

As a means of evaluating market efficiency in foreign exchange options, a comparison of the term structure of implied volatilities to future implied volatilities has an important advantage relative to a comparison of implied volatilities against *realized* volatilities. If implied volatility reflects the market's assessment of price uncertainty in the underlying variable that in fact is not realized, then in small samples implied volatility may be a poor predictor of realized volatility because of "peso problems."[4] In comparing only implied volatilities, however, we require only that the price of this uncertainty evolve rationally over time, not that it actually be realized.

The rest of the article is organized as follows. In Section I, we use the Hull and White (1987) theoretical model of option pricing under stochastic volatility to develop a test of the expectations hypothesis in foreign exchange options, even when prices based on market quotes are formed using a fixed volatility convention. This resolves the apparent contradiction between the convention of using a constant volatility model and the clearly variable volatility reflected in option quotes. Section II examines the data and related descriptive statistics. Section III explicitly tests the expectations hypothesis in volatility quotes using two standard tests. Section IV tests for the presence of "over-reactions" in long-dated volatilities to innovations in short-dated volatilities. Section V concludes.

I. Stochastic Volatility and the Expectations Hypothesis in Implied Volatility

The time-varying nature of volatility might at first seem inconsistent with traders' use of a Black-Scholes option pricing formula, which assumes constant volatility. Given this convention, in the context of stochastic volatility, these quotes do *not* necessarily represent, even under rational expectations, the market's expectation of future volatility. To interpret these volatility quotes in a context that is consistent with changing volatility over time and different volatility at different horizons, one requires a formal model of stochastic volatility.[5] We use the model of Hull and White (1987) to establish the relationship among: (1) the value of an option under stochastic volatility; (2) the bias relative to a corresponding Black-Scholes option price; and (3) the expected variance in the price of the underlying security over the option's

[4] See Lewis (1989) for a discussion of how forecast errors may be systematically incorrect before the market has learned the true process that generates fundamentals.

[5] While our primary motivation is to achieve theoretical consistency, it has also been shown empirically that stochastic volatility models fit foreign exchange options better than a constant volatility model. Bodurtha and Courtadon (1987) find that constant volatility models consistently mispriced foreign exchange options and Melino and Turnbull (1990) show how stochastic volatility models such as Hull and White (1987) fit the data much better than a constant volatility model.

lifetime.[6] Based on these relationships, we develop a coherent framework in which to test the "expectations hypothesis," i.e., an examination of whether the long volatility rate and short volatility rate quoted today are consistent with the short volatility rate quoted in the future. For illustrative purposes, we can focus our attention on the two-period case, denoting the square of the quoted rates as $V_{0,2}$, $V_{0,1}$ and $V_{1,2}$, with subscripts indicating the beginning and end of the time period over which the options apply.

In the Hull and White (1987) model, the underlying asset and its variance follow a geometric Brownian motion. If shocks to the underlying security and to volatility are uncorrelated, and volatility has no systematic risk, then Hull and White (their equation (8)) show that the value at time 0 of a call option expiring at time T can be expressed as:

$$C^{HW}(S, V_0) = \int C^{BS}(\overline{V})h(\overline{V}\,|V_0)\,d\overline{V} \tag{1}$$

where $C^{BS}(\overline{V})$ represents the Black-Scholes option price with volatility $\sigma = \sqrt{\overline{V}}$, h is the conditional distribution of $\overline{V}$, V_t denotes the instantaneous variance (per unit time) at time t, and

$$\overline{V} = \frac{1}{T}\int_0^T V_t\,dt.$$

This result holds because, as the authors show, the value of the option depends only on the mean variance for the lifetime of the option, which is then weighted according to the probability density across possible $\overline{V}$ to determine the option price today.[7]

While the density function h has no closed form solution for the general case, for *at-the-money* options, the concavity of the $C^{BS}(\overline{V})$ function implies that the option price under stochastic volatility (C^{HW}, where initial $V_0 = \overline{V}$) must be lower than $C^{BS}(\overline{V})$. We therefore define this bias for maturity *t as* $\theta_t \equiv C^{HW}/C^{BS}$, where clearly $\theta_0 = 1$.[8]

Assuming that volatilities quoted in the market in fact correspond to options priced according to this stochastic volatility model, then applying the above relationship specifically to the price of two consecutive short-dated

[6] We have chosen to use the relatively well-known Hull and White (1987) model although most of our results are generalizable to other stochastic volatility models, as will be discussed later in this section.

[7] As long as volatility and exchange rate shocks are uncorrelated and there is no volatility risk premium, this result is fairly generalizable, and in fact is common to other models in which variance changes over time. See, for example, Scott (1987, 1992).

[8] Hull and White, through numerical simulations using a fixed interest rate, show that for at-the-money (forward) options, the discrepancy between C_{HW} and C_{BS} is independent of the level of volatility but increases with the time to maturity of the option. See the discussion of Figures 2 and 4 in Hull and White (1987).

options and one long-dated option covering the same period, we obtain:

$$C^{BS}(V_{0,1}) = C_{0,1}^{HW} = \theta_1 C^{BS}\left({}_0\overline{V}_{0,1}\right) \tag{2a}$$

$$C^{BS}(V_{1,2}) = C_{1,2}^{HW} = \theta_1 C^{BS}\left({}_1\overline{V}_{1,2}\right) \tag{2b}$$

$$C^{BS}(V_{0,2}) = C_{0,2}^{HW} = \theta_2 C^{BS}\left({}_0\overline{V}_{0,2}\right) \tag{2c}$$

where the subscript preceding the variable denotes the time at which expectations are taken, and the left-hand most term represents prices observed in the market.

We would like to establish a relationship between V_{ij}, the square of the volatility quoted in the market at time i for an option with expiration date j, and $\overline{V}_{ij}$, the mean variance of the price of the underlying security between times i and j. In order to do this, we need to understand how θ_t, the multiplicative bias, should appear if incorporated into the argument of the Black-Scholes formula. We first note that, for at-the-money options, the Black-Scholes formula is nearly linear in volatility, with the deviation from linearity (as expressed by the magnitude of $\partial^2 C/\partial\sigma^2$) declining for smaller values of σ and approaching zero for $\sigma \to 0$.[9] Since at-the-money options have zero intrinsic value and moreover have a zero intercept with respect to volatility, we can combine these two properties to approximate $\theta_t C^{BS}(\overline{V})$ as $C^{BS}(\theta_t^2 \overline{V})$ since variance behaves as the square of volatility.

Therefore, we can rewrite equations (2a) to (2c) as:

$$C^{BS}(V_{0,1}) = C_{0,1}^{HW} = \theta_1 C^{BS}\left({}_0\overline{V}_{0,1}\right) = C^{BS}\left(\theta_1^2\, {}_0\overline{V}_{0,1}\right) \tag{3a}$$

$$C^{BS}(V_{1,2}) = C_{1,2}^{HW} = \theta_1 C^{BS}\left({}_1\overline{V}_{1,2}\right) = C^{BS}\left(\theta_1^2\, {}_1\overline{V}_{1,2}\right) \tag{3b}$$

$$C^{BS}(V_{0,2}) = C_{0,2}^{HW} = \theta_2 C^{BS}\left({}_0\overline{V}_{0,2}\right) = C^{BS}\left(\theta_2^2\, {}_0\overline{V}_{0,2}\right) \tag{3c}$$

Notice that the far left and far right terms are expressed uniquely in terms of the simple Black-Scholes model, thus enabling us to equate the arguments directly.

To examine an expectations hypothesis in volatility quotes, we compare the current short and long rates with the future short rate. These volatility quotes correspond respectively to $E_0[\overline{V}_{0,1}]$, $E_0[\overline{V}_{0,2}]$, $E_1[\overline{V}_{1,2}]$. We know that by definition

$$E_0\left[t_2 \overline{V}_{0,2}\right] = E_0\left[t_1 \overline{V}_{0,1}\right] + E_0\left[(t_2 - t_1)\overline{V}_{1,2}\right] \tag{4}$$

and by the law of iterated expectations,

$$E_0\left[\overline{V}_{1,2}\right] = E_1\left[\overline{V}_{1,2}\right] + u_1 \tag{5}$$

where u_1 is a white noise error term realized at time t_1.

Combining equations (4), (5), and (3a) to (3c), we obtain:

$$(t_2 - t_1)V_{1,2} = (\theta_1/\theta_2)^2 t_2 V_{0,2} - t_1 V_{0,1} + u_1 \tag{6}$$

[9] In fact, the option price is concave in volatility, but as an empirical matter, this concavity is negligible.

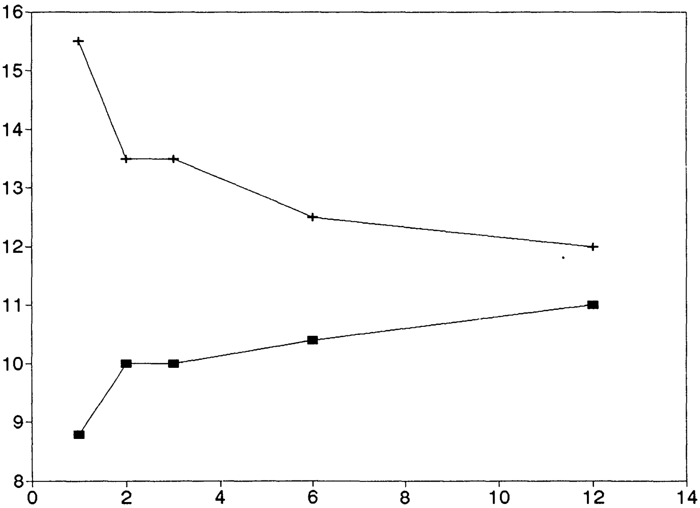

Figure 1. Term Structure of Volatility Quotes. This figure illustrates the form of the term structure of volatility quotes on dollar-pound options with time to expiration of one, two, three, six and twelve months) on two different dates. In June 1990 (■), the term structure slopes upwards while three months later, in September 1990 (+), it slopes downwards.

Assuming $t_2 = 2t_1$, this reduces still further to:

$$V_{1,2} = 2(\theta_1/\theta_2)^2 V_{0,2} - V_{0,1} + u'_1 \tag{7}$$

where $u'_1 = u_1/t_1$.

This equation, which one can refer to as an "expectations hypothesis" in volatility (squared), will be the basis for the test and discussion in Section III of the article.

II. Data and Descriptive Statistics

Daily closing quotes on foreign exchange options, in the form of volatility quotes that traders by agreement substitute into a Garman-Kohlhagen formula (Black-Scholes adjusted for the foreign interest rate), were provided by a commercial bank in London.[10] Since the volatility is the only unobservable parameter in the Black-Scholes formula, these volatilities—representing traders' subjective assessments of future movements in the underlying asset —uniquely determine the option's price. By convention, these quotes are used in pricing the market's most commonly traded instrument: at-the-money forward straddles, i.e., a call and a put with a common strike price equal to the forward exchange rate of the same maturity as the option.[11]

Figure 1 illustrates two general forms for the term structure of volatility

[10] We use the average of the bid and ask quote.

[11] These quotes do not apply to other strike prices or instruments, which are less liquid and for which one must request quotes on a customized basis.

Table I

Descriptive Statistics of Volatility Quotes

This table reports the mean, standard deviation, skewness, kurtosis, minimum, and maximum for the average of daily bid and ask volatility quotes for options with one, two, three, six, and twelve months to expiration for four currency pairs (dollar-mark (*USD-DEM*), dollar-pound (*USD-GBP*), dollar-Swiss franc (*USD-CHF*), and dollar-yen (*USD-JPY*)) for the period December 1, 1989 to August 31, 1992. The number of observations in each series is 717.

Variable	Mean	Std. Dev.	Skewness	Kurtosis	Minimum	Maximum
*USD-GBP*1	11.798	1.5447	0.086	2.256	8.8	15.6
*USD-GBP*2	11.825	1.1326	0.047	2.176	9.5	14.7
*USD-GBP*3	11.816	1.0103	−0.139	2.106	9.8	14.2
*USD-GBP*6	11.838	0.7542	−0.164	2.458	10.0	13.6
*USD-GBP*12	11.873	0.5563	−0.050	2.944	10.3	13.2
*USD-DEM*1	11.934	1.5736	0.196	2.597	8.6	16.0
*USD-DEM*2	11.958	1.2022	0.070	2.492	9.3	15.0
*USD-DEM*3	11.934	1.0910	−0.168	2.411	9.6	14.5
*USD-DEM*6	11.944	0.8202	−0.129	2.581	10.0	13.9
*USD-DEM*12	11.942	0.5999	−0.096	2.497	10.4	13.3
*USD-JPY*1	9.952	1.8877	0.906	2.949	7.0	16.0
*USD-JPY*2	9.849	1.4494	0.894	2.667	7.7	14.0
*USD-JPY*3	9.899	1.3270	0.910	2.741	7.7	14.0
*USD-JPY*6	9.879	0.9312	0.926	2.764	8.2	12.9
*USD-JPY*12	9.890	0.6764	0.794	2.472	8.8	11.7
*USD-CHF*1	12.383	1.5716	0.069	2.173	9.1	16.0
*USD-CHF*2	12.270	1.1637	−0.092	2.246	9.8	15.0
*USD-CHF*3	12.236	1.0682	−0.267	2.219	10.1	14.5
*USD-CHF*6	12.162	0.7961	−0.384	2.515	10.3	14.2
*USD-CHF*12	12.118	0.5628	−0.440	2.751	10.6	13.4

quotes on dollar-pound options with time to expiration of one, two, three, six, and twelve months. In June 1990, the term structure slopes upwards, indicating lower uncertainty per unit time in the near future than in the medium future. Conversely, in September 1990, three months later, short-term uncertainty per unit time is higher than for longer horizons.

At-the-money options hold three key advantages for our testing purposes. First, markets are most liquid in at-the-money or near-the-money options. Second, as discussed in the previous section, the option premium is close to linear in volatility for at-the-money options, simplifying the relationship between quoted volatilities and the option premium. Third, the pricing bias incurred in using the Black-Scholes model rather than the Hull and White (1987) stochastic volatility model is independent of the instantaneous level of volatility for at-the-money forward strike prices.

Table I presents summary statistics based on the average of the bid and ask rates of volatility quotes (percent per year) on one, two, three, six, and twelve month options for four currency pairs (dollar-mark (*USD-DEM*), dollar-pound (*USD-GBP*), dollar-Swiss franc (*USD-CHF*), and dollar-yen

Table II

Autocorrelations and Partial Autocorrelations

This table reports the first 10 autocorrelations and partial autocorrelations for daily volatility quotes from option prices of one, two, three, six, and twelve months to maturity for four currency pairs (dollar-mark (*USD-DEM*), dollar-pound (*USD-GBP*), dollar-Swiss franc (*USD-CHF*), and dollar-yen (*USD-JPY*)) for the period December 1, 1989 to August 31, 1992. The number of observations in each series is 717. * Indicates significance at the 5 percent level.

Panel A: *USD-GBP*

	*USD-GBP*1		*USD-GBP*2		*USD-GBP*3		*USD-GBP*6		*USD-GBP*12	
Lag	Auto	Partial	Auto	Partial	Auto	Partial	Auto	Partial	Auto	Partial
1	0.9608*	0.9608*	0.9687*	0.9687*	0.9763*	0.9763*	0.9797*	0.9797*	0.9834*	0.9834*
2	0.9169*	−0.0804*	0.9330*	−0.0862*	0.9501*	−0.0635	0.9597*	−0.0016	0.9671*	−0.0014
3	0.8766*	0.0254	0.8995*	0.0210	0.9241*	−0.0085	0.9429*	0.0695	0.9534*	0.0749*
4	0.8409*	0.0343	0.8658*	−0.0250	0.9001*	0.0286	0.9277*	0.0327	0.9430	0.0940*
5	0.8063*	−0.0128	0.8315*	−0.0250	0.8744*	−0.0536	0.9121*	−0.0102	0.9331*	0.0135
6	0.7705*	−0.0311	0.7988*	0.0069	0.8469*	−0.0473	0.8950*	−0.0383	0.9219*	−0.0273
7	0.7377*	0.0167	0.7698*	0.0293	0.8220*	0.0355	0.8785*	−0.0144	0.9085*	−0.0645
8	0.7106*	0.0427	0.7431*	0.0094	0.7997*	0.0278	0.8626*	0.0005	0.8947*	−0.0239
9	0.6921*	0.0979*	0.7215*	0.0712	0.7816*	0.0767*	0.8491*	0.0496	0.8813*	−0.0127
10	0.6759*	0.0147	0.7042*	0.0495	0.7640*	−0.0025	0.8342*	−0.0405	0.8678*	−0.0201

Panel B: *USD-DEM*

	*USD-DEM*1		*USD-DEM*2		*USD-DEM*3		*USD-DEM*6		*USD-DEM*12	
Lag	Auto	Partial	Auto	Partial	Auto	Partial	Auto	Partial	Auto	Partial
1	0.9616*	0.9616*	0.9681*	0.9681*	0.9736*	0.9736*	0.9768*	0.9768*	0.9741*	0.9741*
2	0.9208*	−0.0503	0.9370*	−0.0036	0.9468*	−0.0190	0.9544*	0.0069	0.9523*	0.0689
3	0.8823*	0.0101	0.9098*	0.0479	0.9249*	0.0781*	0.9366*	0.0892*	0.9427*	0.2350*
4	0.8495*	0.0546	0.8859*	0.0402	0.9046*	0.0203*	0.9216*	0.0535	0.9336*	0.0495
5	0.8183*	−0.0011	0.8628*	0.0046	0.8850*	0.0111	0.9074*	0.0256	0.9246*	0.0664
6	0.7886*	0.0060	0.8401*	0.0007	0.8643*	−0.0272	0.8928*	−0.0060	0.9147*	−0.0005
7	0.7616*	0.0195	0.8184*	0.0062	0.8432*	−0.0173	0.8781*	−0.0028	0.9038*	−0.0107
8	0.7380*	0.0234	0.7988*	0.0119	0.8249*	0.0325	0.8664*	0.0526	0.8967*	0.0601
9	0.7228*	0.1014*	0.7851*	0.0926*	0.8115*	0.0824*	0.8574*	0.0534	0.8921*	0.0607
10	0.7094*	0.0194	0.7733*	0.0307	0.7975*	−0.0096	0.8487*	0.0164	0.8852*	−0.0042

Table II—*Continued*

Panel C: *USD-JPY*

	USD-JPY 1		*USD-JPY* 2		*USD-JPY* 3		*USD-JPY* 6		*USD-JPY* 12	
Lag	Auto	Partial	Auto	Partial	Auto	Partial	Auto	Partial	Auto	Partial
1	0.9729*	0.9729*	0.9787*	0.9787*	0.9807*	0.9807*	0.9809*	0.9809*	0.9878*	0.9878*
2	0.9441*	−0.0484	0.9565*	−0.0300	0.9606*	−0.0306	0.9660*	0.1004*	0.9778*	0.0862*
3	0.9196*	0.0610	0.9363*	0.0241	0.9424*	0.0366	0.9510*	0.0034	0.9690*	0.0518
4	0.8961*	0.0031	0.9171*	0.0175	0.9248*	0.0038	0.9371*	0.0201	0.9615*	0.0604
5	0.8738*	0.0168	0.8995*	0.0304	0.9084*	0.0247	0.9248*	0.0433	0.9536*	−0.0036
6	0.8520*	−0.0074	0.8826*	0.0062	0.8923*	−0.0013	0.9126*	0.0056	0.9455*	−0.0078
7	0.8341*	0.0646*	0.8691*	0.0685	0.8787*	0.0565	0.9024*	0.0488	0.9398*	0.0963*
8	0.8165*	−0.0143	0.8562*	0.0072	0.8659*	0.0141	0.8928*	0.0259	0.9338*	0.0047
9	0.8023*	0.0732	0.8439*	0.0175	0.8550*	0.0516	0.8856*	0.0684	0.9284*	0.0307
10	0.7873*	−0.0274	0.8303*	−0.0335	0.8427*	−0.0447	0.8757*	−0.0542	0.9230*	0.0136

Panel D: *USD-CHF*

	USD-CHF 1		*USD-CHF* 2		*USD-CHF* 3		*USD-CHF* 6		*USD-CHF* 12	
Lag	Auto	Partial	Auto	Partial	Auto	Partial	Auto	Partial	Auto	Partial
1	0.9599*	0.9599*	0.9678*	0.9678*	0.9729*	0.9729*	0.9767*	0.9767*	0.9776*	0.9776*
2	0.9202*	−0.0126	0.9392*	0.0422	0.9491*	0.0490	0.9568*	0.0674	0.9641*	0.1934*
3	0.8857*	0.0449	0.9110*	−0.0045	0.9260*	0.0028	0.9383*	0.0022	0.9509*	0.0414
4	0.8570*	0.0592	0.8863*	0.0410	0.9058*	0.0448	0.9225*	0.0567	0.9402*	0.0649
5	0.8252*	−0.0502	0.8606*	−0.0201	0.8826*	−0.0598	0.9061*	−0.0079	0.9295*	0.0254
6	0.7948*	0.0115	0.8363*	0.0095	0.8600*	−0.0034	0.8899*	−0.0017	0.9186*	0.0012
7	0.7655*	−0.0005	0.8106*	−0.0290	0.8377*	−0.0036	0.8700*	−0.0860*	0.9055*	−0.0500
8	0.7380*	0.0029	0.7855*	−0.0112	0.8142*	−0.0394	0.8494*	−0.0361	0.8904*	−0.0707
9	0.7194*	0.0977*	0.7655*	0.0636	0.7950*	0.0615	0.8323*	0.0266	0.8760	−0.0413
10	0.6981*	−0.0501	0.7465*	−0.0016	0.7766*	−0.0024	0.8152*	−0.0081	0.8629*	0.0076

(*USD-JPY*)) observed daily from December 1989 to August 1992. Perhaps the most salient feature of the data is the significantly higher variability of volatility quotes on short-dated options compared with long-dated options. The standard deviation (over the full sample period) of the one-month volatility, for example, is 2 to 3 times the standard deviation of the twelve-month volatility for all four bilateral rates against the dollar. Moreover, the standard deviation of the volatility for virtually all the currency pairs is a strictly declining function of the maturity. The range of observations is also a declining function of the maturity: the maximum observation is higher and the minimum observation is lower the shorter the maturity, again indicating the higher variability of short-run relative to long-run volatilities.

Sample statistics for skewness (two-tailed) and kurtosis indicate the presence of significant skewness and kurtosis at the 5 percent level for a number of the volatility series. Negative skewness is found for the three, six, and twelve-month dollar-Swiss franc options. In contrast, dollar-yen options at all five maturities, as well as the one-month dollar-mark option, are positively skewed. The remaining 10 out of 20 time series do not exhibit significant skewness. Significantly negative kurtosis is found for 16 of the 20 time series, indicating "thinner tails" than would be expected under a normal distribution. None of the series are characterized by positive kurtosis.

Autocorrelation functions and partial autocorrelation functions, as shown in Table II, suggest that an AR(1) specification can successfully characterize the statistical behavior of these twenty time series.[12] Most first-order autocorrelation coefficients fall in the range of 0.96 to 0.98, indicating mean-reversion in these series. These coefficients suggest a mean half-life of shocks to volatility of 17 to 34 trading days. Within a currency, the first-order autocorrelation coefficients increase as a function of the option's maturity, indicating a greater degree of persistence. The partial autocorrelations are typically near zero after the first lag, further suggesting that an AR(1) characterization is appropriate. The relatively brief period of data coverage (33 months), as well as the near unit-root characteristics of the AR(1) process, unfortunately preclude the meaningful interpretation of augmented Dickey-Fuller tests for unit roots.

Because of data limitations, we were unable to begin our analysis prior to December 1989. Although data after August 1992 were available to us, we have chosen not to make use of such data. In September 1992, volatility quotes in all four of the markets analyzed rose precipitously, reflecting the uncertainty in global foreign exchange markets, including non-Exchange Rate Mechanism (ERM) currencies, that accompanied the crisis in the ERM. While volatility quotes in the preceding month had risen markedly for the four option markets we examine, the term structure observed in August was relatively flat, and thus failed to predict the dramatic rise in volatility quotes that occurred in September. In the week preceding the devaluation of the

[12] Empirically, the first-order autocorrelations implied by our estimates of higher-order autocorrelations never differ by more than 1 percent from the actual first-order autocorrelation.

pound, short-run volatility quotes rose sharply, resulting in a steeply downward-sloping term structure, suggesting an imminent decline in short-run volatility. In fact, one-month volatility quotes for European currencies against the dollar remained high, and above that of longer horizons, for the rest of the year. This failure suggests that this episode might best be explained by alternative models that incorporate the possibility of regime switching or peso problems, which we believe better characterize this particular period. Therefore, our analysis covers only the December 1989 to August 1992 period.

III. Testing the Expectations Hypothesis

Equation (7) provides us with a relationship among the current short, current long, and future short run volatility quotes. In this equation, the ratio θ_1/θ_2 is greater than one (since $\theta_1 > \theta_2$) and converges towards one as the difference in the maturities of the options declines. For estimation purposes, we will temporarily assume that this term is exactly one. Later in this section, we will discuss the nature of the bias resulting from this approximation. Under this approximation, we can rewrite equation (7) and generalize it to an arbitrary number of periods, k, of arbitrary length m months, and obtain:

$$V_{0,km} = (1/k)E_0\left[\sum_{i=0}^{k-1} V_{im,(i+1)m}\right] \tag{8}$$

In this expression, the current long rate is equal to the average of current and expected future short rates.

Since the level of volatility may have a unit root or follow a near-unit-root process, this equation will be tested in terms of the long-short spread rather than using the levels directly. Subtracting $V_{0,m}$ from both sides of this equation and assuming rational expectations, i.e., that expectational errors are uncorrelated with all information available at time t, this equation can be expressed in a testable form as:

$$(1/k)\sum_{i=1}^{k-1}[V_{im,(i+1)m} - V_{0,m}] = \alpha_0 + \beta_0[V_{0,km} - V_{0,m}] + \sum_{i=1}^{k-1} u_{im} \tag{9}$$

where the u_{im} represent the expectational errors and the change in lower boundary results from canceling $V_{0,m}$ for $i = 0$. In equation (9), we are regressing changes in the short rate against the long-short spread in squared volatility quotes.[13]

[13] The expression used in this test is similar to that used in tests of the expectations hypothesis on the term structure of interest rates. As discussed in Froot (1989), Shiller (1990), and Campbell and Shiller (1991), for example, this literature has typically rejected the expectations hypothesis. In contrast, our tests on the term structure of volatility in most cases do not lead to a rejection of the expectations hypothesis.

This relationship among quoted volatilities has been derived in the context of the Hull and White model, which assumes that the stochastic processes driving the asset and the volatility of the asset are uncorrelated. To determine whether this assumption is appropriate for our data set, we estimated the correlations of daily changes in the spot exchange rate and daily changes in volatility and computed the standard errors of our point estimates. Our estimates of the underlying correlation between spot changes and volatility changes during our sample period were of low magnitude and not significantly different from zero for all currencies.

A second key assumption in Hull and White is the absence of a volatility risk premium. In the absence of an equilibrium model, we are unable to test this assumption directly. Nonetheless, we performed (not reported here) difference-in-means tests across the ten maturity pairs and four currencies, taking into consideration the series' AR(1) characterization and allowing for cross-sectional correlation. For the Swiss franc only, longer-dated options tended to exhibit higher means than their shorter-dated counterparts, but overall, no systematic pattern was detected. In our estimation, we allowed for a constant risk premium by including the term α_0.

The regression results for equation (9) are presented in Table III. In total, we cover *four* currencies and the following *nine* maturity pairs (in months): 2 versus 1, 3 versus 1, 6 versus 2, 6 versus 3, 12 versus 1, 12 versus 2, 12 versus 3, and 12 versus 6. Below each coefficient we report the standard errors corrected for overlapping observations as outlined in Hansen (1982).

If the expectations hypothesis holds, then $\alpha_0 = 0$ and $\beta_0 = 1$. As Table III indicates, most of the estimates of β_0 are in the vicinity of one, indicating that future increases in the short volatility rate behave in line with the expectations hypothesis. We are unable to reject the null hypothesis of $\beta_0 = 1$ in 23 of 36 (64 percent) cases. β is never significantly greater than one and always significantly positive. For almost all the European currencies, β_0 is significantly less than one in 12-1, 12-2, and 12-3 month option pairs. In the case of the yen, however, the expectations hypothesis is rejected for the shorter maturities. The risk premium α_0 does not seem to be important: it is different from zero only for the 12-1, 12-2, and 12-3 month option pairs for the dollar-Swiss franc and 12-1 month option pairs for the dollar-pound.

Table III also provides, for each currency and maturity pair, a Wald test of the joint hypothesis that $\alpha_0 = 0$ and $\beta_0 = 1$. The Wald statistic is adjusted for overlapping observations by the methods outlined in Newey and West (1987). The results from the Wald test are very similar to the t-test for $\beta_0 = 1$. For 12 to 13 cases in which $\beta_0 = 1$ was rejected, the Wald test rejects the null hypothesis. For the dollar-yen, 6 versus 1-month option pair, β_0 is significantly different from one but the Wald test is not rejected because of low estimates and large errors on α_0, which equals zero under the null hypothesis. Conversely, there is only one case, the 12 versus 1-month option pair of the Swiss franc, in which the Wald test is rejected but β_0 is not significantly different from one, indicating that the restriction overall may have been rejected as a result of a highly significantly constant term.

Table III

Tests of the Expectations Hypothesis (Changes in Short-Dated Volatility)

Regression of changes in the square of the volatility quotes for the shorter maturity option on the current spread between the square of the volatility quotes for the long- and short-maturity options. Daily observations cover the period December 1, 1989 to August 31, 1992. V_{ij} is the square of volatility quoted at time i for option with expiration date j. m denotes the maturity (in months) of the short-dated options, and km denotes the maturity (in months) of the long-dated options. The first column indicates the months to expiration of the long- and short-dated options. The standard errors are reported below the parameter estimates and have been corrected for overlapping observations using Hansen (1982). Wald Test refers to the joint hypothesis that $\alpha_0 = 0$ and $\beta_0 = 1$.

$$(1/k)\sum_{i=1}^{k-1}[V_{im,(i+1)m} - V_{0,m}] = \alpha_0 + \beta_0[V_{0,km} - V_{0,m}] + \sum_{i=1}^{k-1} u_{im}$$

	Dollar-Pound			Dollar-Mark			Dollar-Yen			Dollar-Swiss Franc		
Options	α_0	β_0	Wald Test	α_0	β_0	Wald Test	α_0	β_0	Wald Test	α_0	β_0	Wald Test
2 on 1	0.772	0.620*	5.47*	0.532	0.684	2.121	1.712	0.413*	8.646*	2.911	0.605*	6.238*
	2.498	0.164		2.619	0.226		1.874	0.201		2.802	0.194	
3 on 1	1.675	0.919	0.568	1.368	0.909	0.465	2.231	0.568	3.78	4.874	0.898	2.097
	4.194	0.166		4.425	0.203		3.542	0.224		4.965	0.180	
6 on 1	1.938	0.944	0.360	1.270	1.006	0.030	4.217	0.667*	4.350	7.638	1.041	1.030
	6.823	0.152		7.366	0.190		8.655	0.164		7.555	0.142	
6 on 2	0.345	0.917	0.233	0.538	1.115	0.236	0.997	0.632	4.219	3.537	1.127	0.748
	4.578	0.180		4.882	0.243		5.386	0.220		4.823	0.222	
6 on 3	0.151	0.701	3.047	−0.152	0.834	0.379	1.141	0.519*	6.77*	2.123	0.851	0.863
	3.196	0.173		3.531	0.273		3.726	0.206		3.519	0.234	
12 on 1	10.114*	0.830*	29.916*	10.146	0.807*	47.214*	10.168	0.979	1.00	16.622*	0.913	40.194*
	4.862	0.078		6.632	0.084		16.350	0.122		5.465	0.476	
12 on 2	6.488	0.730*	38.234*	7.073	0.747*	53.303*	4.276	0.964	0.331	10.218*	0.850*	65.012*
	3.862	0.108		5.311	0.090		11.620	0.156		4.401	0.072	
12 on 3	5.086	0.651*	51.738*	5.372	0.679*	29.037*	3.897	0.885	1.257	8.153*	0.793*	37.190*
	3.232	0.092		4.576	0.086		9.650	0.136		3.876	0.078	
12 on 6	0.152	0.761	1.156	1.031	0.953	0.080	0.339	0.652	3.24	2.547	0.998	0.702
	3.371	0.228		3.802	0.283		4.546	0.202		3.068	0.170	

* Indicates rejection of the null hypothesis ($\alpha_0 = 0$, $\beta_0 = 1$, and the joint hypothesis $\alpha_0 = 0$ and $\beta_0 = 1$ respectively) at the 5 percent level.

A standard alternative to equation (9) is to test the expectations hypothesis by regressing changes in the long rate on the current long-short spread. Subtracting equation (8), the basic relation between the current long rate and current and future short rates, from the same equation with an m-month lead, one can easily show that if the expectations hypothesis holds, then in the equation below $\alpha_1 = 0$ and $\beta_1 = 1$:

$$V_{m,km} - V_{0,km} = \alpha_1 + \beta_1\left(\frac{1}{k-1}\right)(V_{0,km} - V_{0,m}) + \varepsilon_m \tag{10}$$

Here, we are regressing changes in the long rate against the current long-short spread.[14] Note that if $k = 2$, then $\beta_1 = (2\beta_0 - 1)/2$ and $\alpha_1 = 2\alpha_0$, a relationship one obtains by subtracting $V_{0,m}$ from both sides of equation (10) and rearranging.

The empirical estimates of equation (10) are reported in Table IV. Although none of the point estimates of the coefficients on the current spread are as close to one as those reported in Table III, we are still unable to reject the null hypothesis that these coefficients are significantly different from one for 24 of the 36 cases. In the majority of cases, the current spread of volatility quote provides information of the correct sign concerning future changes in the long rate, even at very short horizons (e.g., one to two months). For 7 of the 12 cases in which the null hypothesis is rejected, primarily longer maturities (except for the *USD-JPY* 1–2), the point estimates are negative, but none are significantly so.

Our sample period in these tests is somewhat brief and might result in a lack of power because of the small number of independent observations, especially for longer maturity options. Unfortunately, we are unable to obtain historical data beginning any earlier than December 1989. Nonetheless, many of the rejections of the null hypothesis occur in tests of longer maturities, precisely those tests in which power is lowest. This suggests that the failure to reject the null in tests on shorter maturities does not arise solely from a lack of power.

We now return to equation (7) in order to determine the effect of the approximation $\theta_1 = \theta_2$ on our estimates of α_0 and β_0. When we allow the parameters θ_1 and θ_2 to differ, equation (9) becomes

$$\begin{aligned}(1/k)\sum_{i=1}^{k-1}[V_{im,(i+1)m} - V_{0,m}] &= \alpha_0 + \beta_0[V_{0,km} - V_{0,m}] \\ &\quad + ((\theta_1/\theta_2) - 1)V_{0,km} + \sum_{i+1}^{k-1} u_{im}. \end{aligned} \tag{11}$$

[14] In estimating this equation, we use (when necessary) the standard approximation of $V_{m,km} \approx V_{m,(k+1)m}$. For example, we use $V_{1,13}$, the square of the observed value of the twelve-month implied volatility, in place of $V_{1,12}$, the square of the unobservable eleven-month implied volatility.

Table IV

Tests of the Expectations Hypothesis (Changes in Long-Dated Volatility)

Regression of changes in the square of the volatility quotes of the long-maturity option on the current spread between the square of the volatility quotes for the long- and short-maturity options. Daily observations for the period December 1, 1989 to August 31, 1992. V_{ij} is the square of volatility quoted at time i for option with expiration date j. m denotes the maturity (in months) of the short-dated options, and km denotes the maturity (in months) of the long-dated options. The first column indicates the months to expiration of the long- and short-dated options. The standard errors are reported below the parameter estimates and have been corrected for overlapping observations using Hansen (1982).

$$V_{m,km} - V_{0,km} = \alpha_1 + \beta_1\left(\frac{1}{k-1}\right)[V_{0,km} - V_{0,m}] + \varepsilon_m$$

	Dollar-Pound		Dollar-Mark		Dollar-Yen		Dollar-Swiss Franc	
....***n*** **and** ***m***	α_1	β_1	α_1	β_1	α_1	β_1	α_1	β_1
2 and 1	1.545	0.240*	1.064	0.368	3.423	−0.174*	5.822	0.210*
	4.996	0.328	5.239	0.452	3.748	0.401	5.605	0.388
3 and 1	1.254	0.813	1.353	0.646	0.017	0.230	2.942	0.719
	3.658	0.412	3.883	0.500	2.732	0.427	4.152	0.431
6 and 1†	−0.199	0.367	−0.293	0.425	0.343	0.251	0.237	0.467
	1.971	0.329	2.294	0.434	1.884	0.290	2.487	0.396
6 and 2†	−1.196	0.449	−1.179	0.716	0.289	0.442	−0.206	0.765
	4.021	0.306	4.400	0.323	3.695	0.374	4.612	0.302
6 and 3	0.302	0.401	−0.303	0.668	2.282	0.039	4.246	0.701
	6.392	0.345	7.062	0.545	7.451	0.412	7.039	0.469
12 and 1†	0.272	−0.097*	0.308	0.092	−0.181	−0.299*	0.362	0.051
	0.854	0.336	1.175	0.505	1.138	0.196	1.242	0.493
12 and 2†	0.947	−0.072*	0.933	0.048*	0.075	−0.016*	0.796	−0.020*
	1.682	0.419	2.340	0.467	2.601	0.220	2.209	0.460
12 and 3†	3.482	−0.046*	3.121	0.116*	1.074	0.272*	3.540	0.474
	3.320	0.477	4.543	0.378	5.600	0.252	4.238	0.367
12 and 6	0.304	0.522	2.063	0.906	0.678	0.304	5.095	0.996
	6.741	0.456	7.603	0.566	9.092	0.404	6.135	0.339

* Indicates rejection of the null hypothesis ($\alpha_1 = 0$ or $\beta_1 = 1$) at the 5 percent level.

† Uses the approximation $V_{m,n-n} = V_{m,n}$.

Our estimation omits the third term on the right-hand side of this equation. Therefore, the reported estimates of α_0 and β_0 are biased.[15] The direction of the bias on the β_0 coefficient depends on the covariance between $(V_{0,km} - V_{0,m})$ and $V_{0,km}$. Empirically, we find this covariance to be *negative* in our sample for all maturity pairs and currencies.

This negative covariance in the data may seem surprising since the longer-dated volatility, $V_{0,km}$, appears with a positive sign in both of these terms. In fact, the sign of this relationship follows naturally from the observed mean-reversion in volatilities. When the long-run volatility is high, the short-run volatility is normally higher (since the long rate incorporates the currently high short rate *and* future reversion towards the mean), implying a negative spread. Hence the negative correlation. Since $\theta_1 > \theta_2$, our estimates of β_0 are biased downward. This downward bias only strengthens our results in which β_0 estimates are significantly positive and close to one.[16]

IV. Overreactions in Foreign Exchange Options

As a further test of the expectations hypothesis, we impose the condition $\alpha_0 = 0$ and $\beta_0 = 1$ in equation (9) and examine the relation between information at time t and the residual expression

$$\sum_{i=1}^{k-1} e_{im} = (1/k) \sum_{i=1}^{k-1} (V_{im,(i+1)m} - V_{0,m}) - (V_{0,km} - V_{0,m}). \tag{12}$$

Under the null hypothesis, and the approximation $\theta_1 = \theta_2$, this residual term should equal white noise, and thus no variables known at time t should have predictive power in a regression where this expression is the dependent variable. Even if we are unable to reject that $\beta_0 = 1$, evidence of predictability of the forecast error based on information known at time t would constitute evidence against the expectations hypothesis.

We test this restriction by regressing this residual term on the square of the current short-term volatility quote. This specification has the advantage that it can be interpreted as a test for overreactions of the current long volatility to changes in the current short volatility. If overreactions are present, then when $V_{0,m}$ is high, $V_{0,km}$ is *too high*, leading to a negative prediction error.[17]

[15] A similar argument holds for α_1 and β_1.

[16] Our inability to reject the null despite this downward bias may prove interesting as a contrast with the empirical evidence on the expectations hypothesis on the term structure of *interest* rates, where it is found that β_0's are significantly less than one, and sometimes indistinguishable from zero.

[17] Relaxing the approximation $\theta_1 = \theta_2$ indicates that our estimated coefficients are upward-biased and should be positive rather than zero under the null hypothesis. This decreases the likelihood that overreactions will be detected. We nonetheless report our findings for comparison with Stein (1989), which is characterized by the same bias.

Stein (1989) performs a similar test on implied volatilities of zero-to-one month and one-to-two month options on the S&P 500 Index, detecting "overreactions" in the long rate.[18] Stein concludes that, although overreactions exist, the mispricing impact on shorter maturities is small but if present for longer maturities, it could lead to much more economically significant mispricings. With data on one-, two-, three-, six-, and twelve-month options, we have a much richer term structure on which to test for overreactions. Furthermore, since we are examining longer maturities, given volatility errors would translate into larger absolute pricing errors in the option premium.[19]

Table V reports the results of regressing the residuals in equation (12) against the short rate.[20] For the four currencies (*USD-GBP*, *USD-DEM*, *USD-JPY*, and *USD-CHF*) and nine maturity pairs examined, 12 of 36 coefficients on the short rate are positive, but none of them is significantly so. Of the 24 negative coefficients, only 3 are significant at the 5 percent level. Although we find slightly more negative coefficients than one would expect under the null hypothesis, especially given the positive bias inherent in the test, this does not provide evidence of systematic overreactions. These results contrast with the findings reported in Stein (1989), which detects overreactions in options on the S&P 500.

V. Summary and Concluding Remarks

After identifying a term structure of volatility based on volatility quotes in foreign exchange options, we test whether current volatility quotes on both long-dated and short-dated options are consistent with future volatility quotes on short-dated options, under the assumption of rational expectations. We perform this test in a theoretically consistent context of stochastic volatility based on the framework of Hull and White (1987). Using daily over-the-counter data for the dollar against the pound, mark, yen, and Swiss franc, we are *unable* to reject the expectations hypothesis in the majority of cases. We

[18] Stein (1989) performs the test in implied volatilities instead of implied variances. This misspecification does not suffice, however, to explain the overreaction effects that he detects.

[19] Two other important differences exist between our data set and Stein's. The options in our sample trade with fixed time-to-expiration; therefore, the term structure test is more exact; the S & P options examined by Stein (1989) have a fixed expiration date, resulting in options of varying maturities. Also, since implied volatilities are quoted directly, the expectations hypothesis becomes more "explicit." In contrast, in markets where the premium is quoted the expectations hypothesis may be less transparent.

[20] As stated earlier, under the expectations hypothesis, the left-hand side of the equation should have zero mean and be uncorrelated with any variables known at time t. As shown above, for some of the currency-maturity pairs in our sample, the means differ from zero because of unequal mean implied volatilities for different maturities. To distinguish this violation from the "overreactions" phenomenon, we run these regressions including a constant on the right-hand side.

Table V

Regression of the Constrained Residual on the Short Rate

Tests for overreactions of the long rate to changes in the short rate. Under the null hypothesis, changes in the square of the shorter maturity volatility quotes minus the correct spread between the square of long- and short-dated volatility quotes should be white noise. This difference is regressed on the square of the current short-term volatility quote. A negative sign indicates that the long-term volatility quote overreacts to changes in the short-term volatility quote. Daily observations for the period December 1, 1989 to August 31, 1992. V_{ij} is the square of volatility quoted at time i for option with expiration date j. m denotes the maturity (in months) of the short-dated options, and km denotes the maturity (in months) of the long-dated options. The first column indicates the months to expiration of the long- and short-dated options. The standard errors are reported below the parameter estimates and have been corrected for overlapping observations using Hansen (1982).

$$\left[(1/k)\sum_{i+1}^{k-1}[V_{im,(i+1)m} - V_{0,m}]\right] - [V_{0,km} - V_{0,m}] = a + b[V_{0,m}] + \sum_{i=1}^{K-1}\varepsilon_{im}$$

	Dollar-Pound		Dollar-Mark		Dollar-Yen		Dollar-Swiss Franc	
Options	a	b	a	b	a	b	a	b
2 on 1	−6.836	0.048	−4.151	0.029	−24.835*	0.240	−11.266	0.073
	21.800	0.145	21.740	0.141	12.370	0.149	22.700	0.140
3 on 1	8.787	−0.062	9.382	−0.065	−8.250	0.079	12.708	−0.082
	12.960	0.078	14.360	0.090	8.178	0.097	15.380	0.085
6 on 1	18.030	−0.124	17.598	−0.119	−7.513	0.070	27.327	−0.172
	22.020	0.135	20.490	0.123	13.040	0.120	21.160	0.115
6 on 2	27.863	−0.194	27.635	−0.188**	−2.530	0.025	36.921*	−0.240*
	18.500	0.130	16.130	0.109	10.420	0.111	18.860	0.118
6 on 3	40.937	−0.330	34.362	−0.284	−14.439	0.136	49.734	−0.372
	36.980	0.263	23.750	0.237	16.330	0.184	37.400	0.246
12 on 1	−7.635	0.055	−5.847	0.042	18.002	−0.160	5.273	−0.034
	12.650	0.061	12.400	0.051	25.120	0.101	10.800	0.049
12 on 2	−5.335	0.039	1.016	−0.007	22.007	−0.208**	10.558	−0.070
	12.540	0.069	11.850	0.076	21.900	0.113	12.970	0.076
12 on 3	−6.739	0.048	1.080	−0.008	17.131	−0.164**	9.220	−0.061
	12.650	0.078	11.000	0.078	18.470	0.098	12.940	0.083
12 on 6	45.961	−0.323	48.875*	−0.337*	32.978	−0.326**	56.183*	−0.374*
	29.450	0.210	19.890	0.145	25.030	0.174	18.490	0.131

* and **, respectively, indicate significance different from zero at the 5 percent and 10 percent levels; 2-tailed tests.

conclude that for all currencies and maturity pairs, current spreads between long-run and short-run volatility *do* predict the right direction of future short-rate and long-rate changes, even at horizons as brief as one month.

We then proceed to test for overreactions of the long-dated volatility to changes in the short-dated volatility. Unlike the results in Stein (1989) for options on the S&P 500 Index, our results indicate the absence of systematic overreactions of the long rate to changes in the contemporaneous short rate.

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