Exchange Rate Risk, Transactions Costs and the Forward Bias Puzzle

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ABSTRACT

We seek to explain the forward bias puzzle by introducing measures of foreign exchange risk and illiquidity in the context of a Vector Error Correction (VECM) model. The structure allows us to explicitly consider the cost and risk of trading to arbitrageurs and, therefore, to account for factors responsible for deviations from the expectations hypothesis. We find that measures of risk aversion and transactions costs mitigate the forward bias puzzle. For many currency pairs, the sign of the forward premium coefficient switches from negative and significant to positive and significant after incorporating lagged values of illiquidity and volatility. For all currency pairs, the forward premium coefficient becomes less negative.

The forward bias is an enduring puzzle in international finance. The forward bias involves a violation of the (risk-neutral) market efficiency hypothesis which states that the forward rate is an unbiased predictor of the spot rate. In fact, existing results imply a perverse behavior: market expectations of future changes in the spot exchange rate, as embodied in the forward market, predict future exchange rate movements in the *wrong* direction (Fama, 1984). In other words, the more the foreign currency is at a premium in the forward market, the more it is expected to depreciate with respect to the home currency.

The existence of the forward bias may be due to investor risk-aversion. In this case, market participants demand a risk premium for holding the foreign currency, in addition to the interest rate differential (as required by uncovered interest rate parity (UIP)). The forward bias coefficient is inefficiently estimated if the forward rate is a function of the unobservable risk premium (Fama, 1984).[1] A large literature is devoted to understanding foreign exchange risk, both in terms of the capital asset pricing model (Adler and Dumas, 1983) and consumption-based asset pricing models (Lucas, 1982). These approaches have failed as they require very high levels of the risk aversion or a high covariance of consumption growth with the spot rate. Thus, Sarno (2005) concludes that "it is hard to explain excess returns in forward exchange by an appeal to risk premia alone."

In this paper, we reexamine the role of the risk premium in explaining the forward bias. Our key innovation is that we do so in the context of vector error correction models (VECM) rather than single equation models (such as Fama (1984)). As pointed out by Clarida and Taylor (1997), such an approach is sufficiently general to be able to incorporate risk aversion or any other "omitted variable." In our specification, the spot return depends on both the error

[1] Bernhart, McNown and Wallace (1999) show, under more general conditions, that many common tests of UIP are non-informative in the presence of omitted risk premium.

correction term (i.e. the forward premium) as well as the one-period lagged value of the realized volatility of spot returns. We find that the spot and forward returns are negatively and significantly related to the volatility. More important, however, we find that, after adding volatility to the VECM, the forward premium coefficient switches from negative and significant to positive and significant for five of the eight currency pairs that we examine. In the remaining cases, the addition of volatility makes the forward bias coefficient substantially less negative, as compared to the case without volatility.

One may interpret volatility as a measure of risk aversion. In this case, our result of a negative association of volatility with spot returns is consistent with Fama (1984), who shows that a negative estimate of the forward bias coefficient implies a negative correlation between the risk premia and the spot return.

As another measure of risk premia, we consider the common component of volatility in multiple exchange rates. It is well known that the forecast errors of different currencies might be correlated. Gweke and Feige (1979) have suggested that these correlations may be due to risk aversion. Mahieu and Schotman (1994) propose a multivariate model for exchange rate volatility, using a factor structure that provides a way to estimate risk premia. Evans and Lyons (2003) find a significant effect of public news on exchange rate volatility; it is then plausible that US macro news induces commonality in the volatility of all currency pairs involving the US dollar. Groen and Balakrishnan (2006) estimate the risk premium of several exchange rates using a conditional factor model for the stochastic discount factor of a representative "worldwide" investor.

We estimate the common volatility measure using a principal components (PC) approach. This approach is related to Mahieu and Schotman (1994) who show that the risk premium is an arithmetic average of (the exponential of) conditional variances of spot returns. In comparison, the PC approach involves the weighted average of conditional variances of returns, where the weights are the PC loadings that provide the greatest total variance. We use the first two PCs of the conditional volatilities of currency pairs (called PCG), where the volatilities are estimated with a GARCH(1,1) model). Consistent with earlier results, we find that incorporating the common volatility PCG results in a positive and significant forward premium coefficient in most cases. The forward premium coefficient is positive in seven of eight currency pairs; and for three currency pairs, the forward premium coefficient is between 0.93 and 0.99.

As our final measure of currency risk premium, we consider the currency risk factors introduced by Lustig, Roussanov and Verdelhan (2008). They show that the currency risk premium are determined by the dollar risk premium RX (i.e. the average interest rate difference between US and foreign currencies) and a carry trade risk premium HML. The latter is constructed by sorting currencies on their forward discounts and then taking the difference in returns between the portfolios with the largest and smallest discounts. We introduce RX and HML into the VECM and find that, while these factors reduce the forward bias, they are not significant in explaining returns. However, when we interact these factors with the PCG factors, then HML is significant but PCG also remains significant. For the euro-USD pair, the forward premium is reduced from -4.30 to 0.92. We conclude that both the Lustig et al (2008) HML risk measure and the PCG measure contain independent information regarding currency risk premia. In particular, PCG incorporates information from all currency pairs whereas HML contains information on the currencies with the highest and lowest forward discounts.

Biased estimates of the forward premium coefficient may also result from transactions costs (Bossaerts and Hillion (1991)). In the context of our VECM structure, one may view increased volatility (which is correlated with illiquidity) as increasing the cost of trading for arbitrageurs and thus making it less likely for the parity relations to hold. To examine this hypothesis, we consider these illiquidity measures: the bid-ask spread, the price impact of trades, and the absolute order flow. We add the lagged value of illiquidity to the VECM and find that all three illiquidity measures are negatively related to the spot and forward returns. Moreover, the addition of illiquidity either turns the forward premium coefficient from negative to positive, or makes it less negative. When we interact volatility with order flow, the volatility remains significant, and the forward premium coefficient becomes more positive. Overall, our results show that accounting for transactions costs and risk aversion results in a reduction in the forward bias and in some cases eliminates it altogether.

We contribute to the literature by introducing measures of foreign exchange risk and illiquidity in the context of a VECM model. The structure allows us to explicitly consider the cost and risk of trading for arbitrageurs and, therefore, to account for factors responsible for deviations from interest rate parity relations. We confirm the intuition of researchers that risk aversion and transactions costs are important determinants of the forward bias puzzle. Indeed, after introducing measures of illiquidity and risk aversion into the VECM, we find that the forward bias is significantly reduced. In most cases, the sign of the forward premium coefficient switches from negative and significant to positive and significant.

The paper is organized as follows. In Section I, we discuss the empirical framework used in the paper. In Section II, we describe our data. In Section III, we present results for the forward bias when accounting for past realized volatility. In section IV, we examine the forward bias in the presence of common volatility across multiple currency pairs. In Section V, we assess the role of transactions costs in explaining the forward puzzle. We conclude in Section VI.

I. Empirical Framework

As is typical, we start with the UIP which states that the expected rate of exchange rate depreciation is just equal to the interest rate differential. The next step is to consider the covered interest rate parity relation which states that the interest rate differential is just equal to the forward exchange rate premium (i.e. the difference between the forward and the spot rates). Combining these two parity relations and assuming rational expectations, we get:

$$s_{t+1} - s_t = \alpha + \beta(f_t - s_t) + \varepsilon_{t+1} \quad (1)$$

where s_t is the log spot exchange rate at time t (the domestic price of the foreign currency), and f_t is the log of the 1-period forward rate at time t. Under the risk-neutral efficient market hypothesis (RNEMH), $\beta=1$ and ε is equal to the rational expectations forecast error.

We follow the framework of Clarida and Taylor (1997), which assumes that deviations from the RNEMH are due to realizations of a stationary stochastic process. Assuming that the spot rate follows a unit root process (an assumption that cannot be rejected in the data), Clarida and Taylor (1997) show that the vector of spot and forward rates should be well represented by a VECM. Further, the system should have exactly one cointegrating vector. Finally, the forward premium f_t-s_t should be a basis for the cointegrating vector.

Assuming that spot and forward rates are integrated of order one (an assumption that we will later verify), we examine a VECM model (Engle and Granger (1987) and Johansen (1991)) for the spot and forward rates. Letting $y_t=[s_t\ f_t]$ denote the vector of the system's variables for a particular currency, the VECM can be written as:

$$\Delta y_t = \mu + \lambda \Delta y_{t-1} + \Pi y_{t-1} + \nu_t \quad (2)$$

where Δ is the first difference operator. We only incorporate first order lags of the differences series since higher order lags were not found to be significant. If the matrix Π is of rank 1, then it can be factored into two matrices α and β such that $\Pi = \alpha\beta^{\prime}$ where $\beta^{\prime}$ is the cointegrating vector and α is the adjustment coefficient. The cointegrating vector defines a long-run relationship between the spot and forward rates to which the system returns after a shock.

We may understand the role of the risk premium in this framework by noting that the risk premium ρ_t can be written as a deviation from RNEMH:

$$\rho_t = f_t - E\left(s_{t+1} \middle| \Omega_t\right) \quad (3)$$

where Ω_t is the information set at time t. Then, rearranging (3), we have:

$$f_t - s_t = E\left(s_{t+1} - s_t \middle| \Omega_t\right) + \rho_t \quad (4)$$

Thus, the forward premium is the optimum forecast of the spot return plus the risk premium. More generally, ρ_t may be interpreted as *any* deviation from RNEMH. In subsequent analysis, we will consider the hypothesis that ρ_t may incorporate transactions costs in addition to a risk premium.

We introduce volatility and illiquidity measures into the VECM by assuming that they are exogenous to the system. This is consistent with the empirical framework described in (3). Consider the expanded information set $\Omega_t^{\prime}$=[Ω_t, X_t] where X_t is a measure of risk aversion (e.g. realized volatility). If investors are risk neutral, $E(s_{t+1}| \Omega_t^{\prime}) = E(s_{t+1}| \Omega_t)$ and X_t has no predictive power for spot returns. However, if investors are risk averse, then:

$$E\left(s_{t+1} \middle| \Omega_t^{\prime}\right) = E\left(s_{t+1} \middle| \Omega_t\right) + E\left(s_{t+1} - E\left(s_{t+1} \middle| \Omega_t\right) \middle| X_t - E\left(X_t \middle| \Omega_t\right)\right) \quad (4)$$

The second term is the projection of the spot forecast error on the orthogonalized part of X_t. If this term is non-zero, then X_t has information not contained in Ω_t that helps to predict spot returns.

Accordingly, let the vector of exogenous variables $X_t=[x_{ht}, x_{ft}]$, where x_{it} is the exogenous variable for country i=h, f. We modify the VECM as follows:

$$\Delta y_t = \mu + \lambda \Delta y_{t-1} + \Pi y_{t-1} + \delta X_{t-1} + \nu_t \tag{5}$$

Our particular interest is the estimate of the adjustment coefficient α_s in the regression of Δs_t on the forward premium (f_t-s_t). If risk-aversion helps explain the forward bias, then introducing X_{t-1} into the VECM should move α_s closer to 1.

We note that X_t may also enter VECM through the cointegrating vector. This would be the case if X_t affects the spot and forward returns via the forward premium *only*. In this case, volatility should be cointegrated with the spot and forward rates, which we can reject in the data. Therefore, in this paper, we allow X_t to have a marginal impact on the spot and forward returns directly, beyond any indirect effects via the forward premium.

While in the above discussion, we have identified X_t with risk-aversion, X_t need not have this specific interpretation. It can be anything that is informative returns, as discussed in Clarida and Taylor (1997). In particular, we allow X_t to be various measures of illiquidity variables, such as the bid-ask spread or the price impact.

II. Data

From Datastream, we obtain the bilateral forward and spot exchange rates for eight currency pairs. We have six US dollar (USD) based exchange rates: the USD vis-a-vis the Australian dollar, the euro (German mark before 1999), the Japanese yen, the British pound, the Canadian dollar and the Swiss franc. These exchange rates are expressed in USD per unit of the other currency. We further have two euro-based exchange rates: the euro vis-a-vis the pound and the yen. These exchange rates are in euros per unit of the other currency. The USD/EUR currency pair is expressed in euros per USD.

The sample period spans December 1996 to February 2008 for a total of 135 monthly observations. An observation consists of forward and spot rates on the last trading day of each month. We also use intra-day high-frequency tick data to calculate the realised volatility, which is the sum of squared log returns based on 5-minute time intervals. This is constructed as follows. For each 5-minute period, we take the last FXFX Reuters midquote price (the average of the representative ask and bid quotes). To ensure accuracy of the volatility estimates, we have compared the Reuters indicative quotes with firm quotes from the Electronic Brokerage Services (EBS) on the EUR/USD, AUD/USD, GBP/USD, CHF/USD and USD/JPY spot exchange rates over the same sample period. The use of Reuters and EBS data essentially provides the same estimation of realised volatility.

III. The Forward Bias and the Realized Volatility

In this section we describe the results of estimating the VECM model with and without incorporating information about lagged realized volatility to predict spot and forward returns. We confirm that, without volatility, the forward bias puzzle exists, as documented in existing literature. We then show that incorporating volatility substantially mitigates the forward bias puzzle. We first present results for the USD-Euro exchange rate and then show robustness by extending the results to seven additional pairs.

Section A shows descriptive statistics for the USD-euro exchange rate. Section B shows VECM results for the USD-euro exchange rate and for seven other exchange rates.

A. Descriptive Statistics

INSERT TABLE 1 HERE

Table 1 shows basic descriptive statistics for the USD-Euro exchange rate. The table shows moments of the distribution of the spot and forward returns, the forward premium and the realized volatility, and the correlation matrix between the variables. Fama (1984) and others have noted the "omitted variable" problem in estimating equation (1). If there is an omitted variable in the equation, and the forward premium is correlated with this variable, then the forward premium coefficient β is biased. We note from Table 1 that the forward premium has a positive correlation of 0.17 with volatility. This suggests that the volatility may be a relevant omitted variable (as we hypothesize).

Fama (1984) further states that two conditions must be true in order for an omitted variable (such as a risk premium) to explain a negative coefficient on the forward premium. First, the variance of the risk premium must be greater than the variance of the spot return forecast error [i.e. $E(s_{t+1}) - s_t$]. Also, the covariance of the risk premium and the forecast error should be negative. Of course, the forecast error is not directly observable. Instead we show the spot return under the assumption that the spot return approximates the forecast error [i.e. $E(s_{t+1}) = s_{t+1}$]. For convenience we show in Table 1 both $(s_{t+1} - s_t)$ and $(s_t - s_{t-1})$. If the realized volatility is a measure of the risk premium, then both of Fama's (1984) conditions appear to be satisfied. In particular, the standard deviation of the realized volatility (0.406) exceeds that of the spot return (0.306) and the two variables are negatively correlated (-0.11).

B. VECM Results

INSERT TABLE 2 HERE

In Table 2, we present results from estimating the VECM model for the USD-euro currency pair. The first panel of Table 2 shows that, consistent with previous literature, there is exactly one cointegrating vector, as hypothesized. Specifically, we reject the null of no cointegrating vectors but cannot reject the null of at most one cointegrating vector. Panel B of Table 2 reports the estimation results. The first two columns shows results without incorporating realized volatility. Consistent with earlier literature, we find that the error correction (EC) coefficient (i.e. the coefficient on the forward premium) is -4.3 when the dependent variable is the spot return. Interest rate parity requires that this coefficient should be 1. Thus, not only is the coefficient different from 1, but it is the wrong sign! This is the well-documented forward bias puzzle. In the next two columns of Table 2, we add one lag of the differenced series. These terms are not statistically significant and the EC coefficient remains about the same.

In the final two columns of Table 2, we add the one-period lag of the realized volatility of spot returns. We find that the sign is negative and significant in both the spot and forward return equations. If we interpret volatility as a risk premium, this result is consistent with Fama's (1984) requirement of a negative correlation between the risk premium and the expected change in the spot rate. Most important, the EC coefficient is now *positive* and significant. In particular, it is 0.23 in both the forward and spot equations. Thus, incorporating information about the lagged volatility, substantially mitigates the forward bias puzzle.

INSERT TABLE 3 HERE

Do our results hold for other currency pairs? In Table 3, we present results from estimating the VECM model for several major currency pairs: USD-Australian dollar (AUD), USD-British Pound (GBP), USD-Canadian dollar (CAD), USD-Swiss franc (CHF), USD-Japanese Yen (JPY), Euro-GBP and Euro-JPY. For most of the currency pairs, we find that incorporating the realized volatility helps mitigate the forward bias puzzle. The first three rows of the table shows results without incorporating realized volatility. We find that the EC coefficient is negative for all currency pairs and significant for four currency pairs. The magnitude ranges from -0.5 to about -5. The next rows show results after incorporating lagged volatility. Now the EC coefficient is positive for five of the eight currency pairs and it is significant for four of these five pairs. The magnitude of the EC coefficient is between 0.23 and

0.28 for three of the pairs, almost 4 for another pair and exceeds 20 for the Euro-JPY pair. The coefficient of the realized volatility is significant in four cases, with two positive and two negative signs.

In summary, we find consistent evidence that incorporation of lagged realized volatility of the spot returns help to mitigate the forward bias puzzle, in the sense of making the forward premium coefficient positive or less negative. An interpretation of the result is that the volatility is a measure of the risk-premium and accounts for deviations from the interest parity relation due to risk aversion of investors.

IV. The Forward Bias and Common Volatility

In this section, we provide further evidence that accounting for the risk premium helps to mitigate the forward bias puzzle. Previously, we had used the realized volatility as a proxy for the risk premium, but it is open to multiple interpretations. For example, to the extent that volatility is correlated with illiquidity, it may also be related to illiquidity. We now provide alternative measures of risk premium to assess the robustness of our results.

As another measure of risk premia, we consider the common component of volatility in multiple exchange rates. It is well known that the forecast errors of different currencies might be correlated. Gweke and Feige (1979) have suggested that these correlations may be due to risk aversion. Mahieu and Schotman (1994) propose a multivariate model for exchange rate volatility, using a factor structure that provides a way to estimate risk premia. Evans and Lyons (2003) find a significant effect of public news on exchange rate volatility; it is then plausible that US macro news induces commonality in the volatility of all currency pairs involving the US dollar. Groen and Balakrishnan (2006) estimate the risk premium of several exchange rates using a conditional factor model for the stochastic discount factor of a representative "worldwide" investor.

We estimate the common volatility measure using a principal components (PC) approach. This approach is related to Mahieu and Schotman (1994) who show that the risk premium is an arithmetic average of (the exponential of) conditional variances of spot returns. In comparison, the PC approach involves the weighted average of conditional variances of returns, where the weights are the PC loadings that provide the greatest total variance.

Intuitively, the PC relates to the co-movement in the variance of exchange rate returns. Thus, our first measure of "common volatility" is the PC of the realized volatility of the currency pairs we have examined previously. We extract the first two PCs of the realized volatilities of the eight currency pairs. These two components explain about 71% of the proportion the total variance explained (49% and 22%, respectively).

Our second measure of "common" volatility consists of the first two PCs of the conditional volatilities of currency pairs. For each spot exchange rate, we perform a GARCH(1,1) regression by regressing the exchange rate return on a constant and thereby obtain eight conditional variance series. In order to capture the co-movement in these series, we calculate the Principal Component based on the ordinary (Pearson) correlation matrix, and normalised loadings. The first two PCs cover 73% of the proportion of total variance explained (38% and 35%, respectively).

INSERT TABLE 4 HERE

Table 4 shows descriptive statistics of the PCs of realized volatility (PCRV) and conditional volatility (PCG). The correlation matrix shows that PCRV has correlation of more than 0.90 with realized volatility, as expected. PCG is also correlated with the realized volatility, although the correlation is lower at 0.68. PCRV and PCG have a correlation of 0.68. Similar to realized volatility, PCRV and PCG have negative correlation with the forward premium and positive correlation with spot returns.

INSERT TABLE 5 HERE

Table 5 shows estimates of the VECM model for eight currency pairs after incorporating lagged values of PCRV. The first three columns of the table repeat the previous results of the VECM estimations without volatility. The next columns repeat the estimations using lagged values of PCRV. Estimates of the coefficients of PCRV are generally not significant but, similar to realized volatility, its incorporation help to mitigate the forward bias puzzle. The EC coefficient becomes less negative in every case. In four out of eight cases, the coefficient switches from negative to positive.

INSERT TABLE 6 HERE

Table 6 shows estimates of the VECM model for eight currency pairs after incorporating lagged values of PCG. The final seven columns show the estimations using lagged values of PCG. In contrast to PCRV, the estimates of the PCG1, the first principal component, is significant in 6 out of 8 cases, although it is not economically meaningful to interpret the signs. The addition of lagged values of PCG substantially mitigates the forward bias puzzle. The EC coefficient becomes positive in 7 out of 8 cases. In 4 out of these 7 currency pairs, the positive coefficient is also statistically significant. In addition, for three currency pairs, the forward premium coefficient is between 0.93 and 0.99; for a fourth currency pair, the forward premium coefficient is 1.39. These results provide strong support to the notion that risk premia account for deviations of the forward rate from the expected spot rate.

As our final measure of currency risk premia, we consider the currency risk factors introduced by Lustig, Roussanov and Verdelhan (2008). They show that the currency risk premia are determined by the dollar risk premium RX (i.e. the average interest rate difference between US and foreign currencies) and a carry trade risk premium HML. The latter is constructed by sorting currencies on their forward discounts and then taking the difference in returns between the portfolios with the largest and smallest discounts.

INSERT TABLE 7 HERE

In Table 7, we introduce RX and HML into the VECM for the Euro-USD currency pair. We find that (see column labeled VECM-CRF) while RX and HML reduce the forward bias, they are not significant in explaining returns. However, when we interact these factors with the PCG factors (see column labeled VECM-CRF-PCG), then HML is negative and significant but PCG also remains significant. The forward premium is reduced from -4.30 to 0.92. We conclude that both the Lustig et al (2008) HML risk measure and the PCG measure contain independent information regarding currency risk premium. In particular, PCG incorporates information from all currency pairs whereas HML contains information on the currencies with the highest and lowest forward discounts.

In this section, we have provided additional evidence for the possibility that our measures of volatility (i.e. realized volatility of particular currencies, a common volatility for multiple currency pairs, and a carry trade risk factor from Lustig et al (2008)) are measures of risk premia. After incorporating lagged information about volatility, the forward bias is substantially mitigated, especially when using the PCG measure. However, we cannot rule out the idea that some notion of illiquidity is also driving our results. We turn to this issue next.

V. The Forward Bias and Transactions Costs

Biased estimates of the forward premium coefficient may also result from transactions costs (Bossaerts and Hillion (1991)). In the context of our VECM structure, one may view increased volatility (which is correlated with illiquidity) as increasing the cost of trading for arbitrageurs and thus making it less likely for the parity relations to hold. To examine this hypothesis, we consider these illiquidity measures: the bid-ask spread, the price impact of trades, and the absolute order flow. We add the lagged value of illiquidity to the VECM and consider the effects on the forward premium coefficient. We also consider the interaction of volatility and illiquidity measures.

INSERT TABLE 8 HERE

Table 8 shows estimates of the VECM model after incorporating lagged values of illiquidity. For brevity, we only show results for the USD-euro pair. The first two columns of the table repeats the previous results of the VECM estimations without volatility and with realized volatility. The next columns show the estimations using lagged values of the bid-ask spread, the absolute order flow and the price impact. Except for the spread, the illiquidity measures have negative and significant coefficients, similar to volatility. The forward premium coefficient becomes less negative in all cases. Thus, transactions costs can also help explain deviations of the forward rate from the expected spot rate.

Next, we examine whether transactions costs drive out the power of volatility to account for the forward bias. The last 3 columns incorporate both realized volatility and one of the illiquidity measures. We find that in 2 of 3 cases, the volatility remains negative and significant. Also, in 2 of 3 cases, the forward bias is further reduced, relative to when either the volatility or transactions cost measures were used separately.

We conclude in this section that both risk premia and transactions costs have the ability to explain deviations from the parity relation. Both factors relate to the role of arbitrageurs. The presence of risk aversion makes arbitrage risky. The presence of transactions costs makes arbitrage costly. The effect of each is to make it harder for arbitrageurs to maintain the long-run equilibrium relation between the spot and forward markets in the short run.

VI. Conclusion

The forward bias is an enduring puzzle in international finance. It is a violation of the (risk-neutral) market efficiency hypothesis which states that the forward rate is an unbiased predictor of the spot rate. In this paper, we reexamine the role of the risk premium in explaining the forward bias. Our key innovation is that we do so in the context of vector error correction models (VECM) rather than single equation models (such as Fama (1984)). In our specification, the spot return depends on both the error correction term (i.e. the forward premium) as well as the one-period lagged value of the realized volatility of spot returns.

We find that the spot and forward returns are negatively and significantly related to the volatility. More important, however, we find that, after adding volatility to the VECM, the forward premium coefficient switches from negative and significant to positive and significant for five of the eight currency pairs that we examine. In the remaining cases, the addition of volatility makes the forward bias coefficient substantially less negative, as compared to the case without volatility.

As another measure of risk premia, we consider the common component of volatility in multiple exchange rates. We estimate the common volatility measure using a principal components (PC) approach. We use the first two PCs of the conditional volatilities (estimated with a GARCH(1,1) model) of currency pairs. Consistent with earlier results, we find that incorporating common volatility results in a positive and significant forward premium coefficient in most cases. The forward premium coefficient is positive in seven of eight currency pairs; and for three currency pairs, the forward premium coefficient is between 0.93 and 0.99.

As our final measure of currency risk premia, we consider the currency risk factors introduced by Lustig, Roussanov and Verdelhan (2008). They show that the currency risk premia are determined by the dollar risk premium RX (i.e. the average interest rate difference between US and foreign currencies) and a carry trade risk premium HML. We find that while RX and HML reduce the forward bias, they are not significant in explaining returns. However, when we interact these factors with the PCG factors, then HML is negative and significant but PCG also remains significant. The forward premium is reduced from -4.30 to 0.92 for the Euro-USD currency pair. We conclude that both the Lustig et al (2008) HML risk measure and the PCG measure contain independent information regarding currency risk premium. In particular, PCG incorporates information from all currency pairs whereas HML contains information on the currencies with the highest and lowest forward discounts.

Biased estimates of the forward premium coefficient may also result from transactions costs (Bossaerts and Hillion (1991)). In the context of our VECM structure, one may view increased volatility (which is correlated with illiquidity) as increasing the cost of trading for arbitrageurs and thus making it less likely for the parity relations to hold. To examine this hypothesis, we consider these illiquidity measures: the bid-ask spread, the price impact of trades, and the absolute order flow. We add the lagged value of illiquidity to the VECM and find that all three illiquidity measures are negatively related to the spot and forward returns. Moreover, the addition of illiquidity either turns the forward premium coefficient from negative to positive, or makes it less negative. When we interact volatility with order flow, the volatility remains significant, and the forward premium coefficient becomes more positive. Overall, our results show that accounting for transactions costs and risk aversion results in a reduction in the forward bias and in some cases eliminates it altogether.

We contribute to the literature by introducing measures of illiquidity and risk aversion in the context of a VECM model. The structure allows us to explicitly consider the cost of and the risk to arbitrageurs and, therefore, to account for factors responsible for deviations from interest rate parity relations. We confirm the intuition of researchers that risk aversion and transactions costs are important determinants of the forward bias puzzle. Indeed, after introducing measures of illiquidity and risk aversion into the VECM, we find that the forward bias is significantly reduced. In most cases, the sign of the forward premium coefficient switches from negative and significant to positive and significant.

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Table1: Descriptive statistics and correlation between return and realized variance

The upper part of table 1 shows the descriptive statistics of monthly return of log EURUSD spot rates (RETSS), different between 1-month forward and spot exchange rates (RETSF) and the log of realized volatility based on squared log spot returns over all the 5-minute intervals of the month (LNRV). The lower part of the table shows the (Pearson) correlation coefficients between LNRV, RETSF, RETSS and RETSS1 where the latter is the spot exchange rate return one month ahead. The sample period spans from 1999 to February 2008. *, ** and *** means t-test significance levels at 10%, 5% and 1%, respectively.

	LNRV	RETSF	RETSS
Mean	-4.491	0.006	0.025
Median	-4.465	0.009	0.003
Maximum	-3.399	0.032	0.908
Minimum	-5.533	-0.018	-0.586
Std. Dev.	0.406	0.016	0.306
Skewness	-0.009	-0.129	0.322
Kurtosis	2.955	1.449	2.897
Jarque-Bera prob	0.995	0.003	0.378

Correlation matrix

	LNRV	RETSF	RETSS	RETSS1
LNRV	1			
RETSF	0.17	1		
RETSS	-0.11	-0.26***	1	
RETSS1	-0.17*	-0.27***	0.20*	1

Table 2: Cointegration test and VECM models for EURUSD exchange rates

The panel A of the table shows the Johansen cointegration test between EURUSD forward and spot exchange rates over the sample period from 1999 to February 2008. An intercept is allowed in the cointegration equation and four lags are included in the VAR regression. The panel B of the table shows the estimated coefficients from three Vector Error Correction models, which are named "BM" (referring to the Benchmark Model with no exogenous or autoregressive variables), "BM-AR" (Benchmark model with 1 lag of autoregressive variables) and "VECM-RV". The latter is the Vector Error Correction specification where the exogenous variable is the log of the realized volatility of the previous month, which is calculated on basis of the sum of squared log spot returns over 5-minute intervals (LNRV). T-statistics are in parenthesis and the last row reports the Adjusted R-squared tests.

Panel A: Cointegration test

Hypothesized No. of CE(s)	Eigenval.	Max-Eigen Stat	Prob.**
None *	0.140	15.981	0.027
At most 1	0.000	0.000	0.990

Panel B: VECM	BM Fwd	BM Spot	BM-AR Fwd	BM-AR Spot	VECM-RV Fwd	VECM-RV Spot
EC coeff	-4.311	-4.289	-3.683	-3.660	0.228	0.230
	[-2.36]	[-2.35]	[-1.92]	[-1.91]	[2.33]	[2.36]
Const	0.002	0.002	0.002	0.002	-0.125	-0.125
	[0.88]	[0.88]	[1.01]	[1.01]	[-2.25]	[-2.25]
retsf_t-1			12.722	12.678	24.033	24.141
			[1.28]	[1.28]	[1.76]	[1.77]
retss_t-1			-12.593	-12.549	-23.839	-23.947
			[-1.26]	[-1.26]	[-1.75]	[-1.76]
lnrv_t-1					-0.018	-0.018
					[-2.27]	[-2.27]
Adj. R-sq.	0.040	0.040	0.051	0.050	0.087	0.087

Table 3: VECM models and realized volatility

This table shows the estimated coefficients from Vector Error Correction (VECM) estimations for eight currency pairs on a monthly frequency (USDAUD, USDGBP, USDCAD, USDCHF, USDJPY, USDEUR, EURGBP and EURJPY). Rates are expressed in terms of foreign currencies per US dollar and per euro expect for USDEUR (i.e. euros per US dollar). The VECM endogenous variables are the (log) 1-month forward and spot exchange rates. In the benchmark model ("BM") no exogenous and autoregressive variable is used. In VECM-RV, the exogenous variable is the log of the realized volatility of the previous month, which is calculated on basis of the sum of squared log spot returns over 5-minute intervals (called "OwnRV"). T-statistics and R-squared tests are also reported. The sample period spans from December 1996 to February 2008 (the German mark replaced the euro before 1999).

BM				**VECM-RV**				
	EC	Tstat	R-sq.	EC	Tstat	OwnRV	Tstat	R-sq.
USDAUD	-4.86	-2.65	0.05	0.22	0.88	-0.05	-0.12	0.02
USDGBP	-1.43	-0.77	0.00	-0.13	-0.12	0.37	1.39	0.04
USDCAD	-3.28	-1.79	0.02	-2.68	-1.38	0.02	0.07	0.03
USDCHF	-3.62	-1.92	0.03	-0.02	-2.05	1.69	2.19	0.07
USDJPY	-0.47	-2.40	0.04	0.28	2.15	-0.20	-0.33	0.06
USDEUR	-4.29	-2.35	0.05	0.23	2.36	0.02	2.27	0.02
EURGBP	-2.01	-0.66	0.00	3.88	1.85	-0.32	-1.78	0.04
EURJPY	-0.50	-0.11	0.00	20.03	2.31	-1.52	-2.60	0.03

Table 4: Descriptive statistics and correlation on principal components of volatility

The upper part of the table shows the descriptive statistics of monthly time series corresponding to Principal Components of the realized volatility ("PCRV") and GARCH variance series ("PCG"). The principal components are calculated using eight currency pairs (USDAUD, USDGBP, USDCAD, USDCHF, USDJPY, USDEUR, EURGBP and EURJPY). PCRV is based on the realized volatilities calculated as squared log spot returns over 5-minute intervals of the month. PCG is based on the eight GARCH variance series coming from GARCH(1,1) regressions in which individual spot exchange rate returns are regressed on a constant. The lower part of the table shows the correlation coefficients between PCRV, PCG, RETSF, RETSS and RETSS1. RETSS (RETSS1) is the contemporaneous (1-month ahead) EURUSD spot exchange rate return. RETSF is the difference between log EURUSD forward and spot rates. . *, ** and *** means t-test significance levels at 10%, 5% and 1%, respectively.

	PCRV	PCG
Mean	-0.387	-0.537
Median	-0.276	-0.727
Maximum	3.100	1.733
Minimum	-3.521	-2.743
Std. Dev.	1.522	1.261
Skewness	0.143	0.297
Kurtosis	2.253	1.978
Jarque-Bera prob	0.293	0.040

Correlation matrix

	PCRV	PCG	RETSF	RETSS	RETSS1
PCRV	1				
PCG	0.66***	1			
RETSF	0.18*	0.43***	1		
RETSS	-0.147326	-0.26***	-0.26***	1	
RETSS1	-0.24***	-0.25***	-0.27***	0.20*	1

Table 5: VECM models and principal component of realized volatility

This table shows the estimated coefficients from Vector Error Correction (VECM) estimations for eight currency pairs on a monthly frequency. Rates are expressed in terms of foreign currencies per US dollar and per euro expect for USDEUR (i.e. euros per US dollar). The endogenous variables in the VECM specifications are the (log) 1-month forward and spot exchange rates. In the benchmark model ("BM") no exogenous and autoregressive variable is used. In VECM-PCRV, the exogenous variables are the first two Principal Components of realized volatilities for the eight currency pairs considered in this study. T-statistics and R-squared tests are also reported. The sample period spans from December 1996 to February 2008 (the German mark replaced the euro before 1999).

BM				**VECM-PCRV**						
	EC	Tstat	R-sq.	EC	Tstat	PCRV1	Tstat	PCRV2	Tstat	R-sq.
USDAUD	-4.86	-2.65	0.05	-0.14	-2.43	0.21	1.34	-0.47	-1.80	0.07
USDGBP	-1.43	-0.77	0.00	-0.41	-1.61	0.27	2.25	-0.17	-0.83	0.07
USDCAD	-3.28	-1.79	0.02	-0.71	-0.40	0.04	0.34	-0.11	-0.65	0.02
USDCHF	-3.62	-1.92	0.03	0.13	1.57	0.26	1.59	-0.12	-0.42	0.05
USDJPY	-0.47	-2.40	0.04	-0.05	-2.38	0.00	-0.01	-0.12	-0.47	0.06
USDEUR	-4.29	-2.35	0.05	0.44	1.37	-0.49	-2.15	-0.11	-0.36	0.12
EURGBP	-2.01	-0.66	0.00	3.11	1.17	-0.19	-1.18	-0.17	-0.94	0.04
EURJPY	-0.50	-0.11	0.00	0.86	0.11	-0.20	-1.01	-0.25	-0.73	0.05

Table 6: VECM models and principal component of realized GARCH volatility

This table shows the estimated coefficients from Vector Error Correction (VECM) estimations for eight currency pairs on a monthly frequency. Rates are expressed in terms of foreign currencies per US dollar and per euro expect for USDEUR (i.e. euros per US dollar). The endogenous variables in the VECM specifications are the (log) 1-month forward and spot exchange rates. In the benchmark model ("BM") no exogenous and autoregressive variable is used. In VECM-PCG, the exogenous variables are the first two Principal Components (PCG1 and PCG2) based on the eight GARCH variance series coming from GARCH(1,1) regressions in which individual spot exchange rate returns are regressed on a constant. T-statistics and R-squared tests are also reported. The sample period spans from December 1996 to February 2008 (the German mark replaced the euro before 1999).

BM				**VECM-PCG**						
	EC	Tstat	R-sq.	EC	Tstat	PCG1	Tstat	PCG2	Tstat	R-sq.
USDAUD	-4.86	-2.65	0.05	0.93	0.55	-0.53	-2.50	0.27	1.66	0.08
USDGBP	-1.43	-0.77	0.00	-1.82	-2.17	0.28	2.34	-0.23	-2.07	0.09
USDCAD	-3.28	-1.79	0.02	2.51	0.92	0.46	2.38	-0.11	-0.96	0.08
USDCHF	-3.62	-1.92	0.03	1.39	1.02	0.37	1.69	-0.17	-0.69	0.03
USDJPY	-0.47	-2.40	0.04	0.99	2.38	0.23	1.27	-0.17	-0.91	0.05
USDEUR	-4.29	-2.35	0.05	0.96	2.85	1.07	3.45	-0.13	-0.73	0.16
EURGBP	-2.01	-0.66	0.00	5.38	2.72	-0.57	-2.82	0.01	0.09	0.11
EURJPY	-0.50	-0.11	0.00	0.73	4.19	-1.80	-4.77	-0.02	-0.12	0.21

Table 7: VECM models and the carry trade risk factor

This table shows the estimated coefficients from Vector Error Correction (VECM) estimations for the Euro-USD currency pair (USDEUR) monthly frequency. Rates are expressed in terms of foreign currencies per US dollar and per euro expect for USDEUR (i.e. euros per US dollar). The endogenous variables in the VECM specifications are the (log) 1-month forward and spot exchange rates. In the benchmark model ("BM") no exogenous and autoregressive variable is used. In VECM-CRF the exogenous variables are the dollar risk factor RX and a carry trade risk factor CRF where RX is the average interest rate difference between the US dollar and the Euro. CRF is constructed by sorting currencies based on their forward discounts and then estimating the return difference between the currency pairs with the highest and lowest forward discounts. In VECM-CRF-PCG, we also include the first two Principal Components (PCG1 and PCG2) based on the conditional variances of eight currency pairs (USDAUD, USDGBP, USDCAD, USDCHF, USDJPY, USDEUR, EURGBP and EURJPY). The variances are estimated from GARCH(1,1) regressions in which individual spot exchange rate returns are regressed on a constant. The sample period spans from December 1996 to February 2008 (the German mark replaced the euro before 1999).

	BM	VECM-CRF	VECM-CRF-PCG
EC coeff	-4.289	-3.492	0.924
	-2.346	-1.786	2.740
RX	-	0.101	0.000
		0.347	0.088
HML	-	-0.220	-0.003
		-0.629	3.414
PCG1	-	-	1.082
			3.401
PCG2	-	-	-0.122
			-0.679
Adj. R-sq.	0.039	0.036	0.115

Table 8: VECM models, volatility and liquidity

This table shows the estimated coefficients from eight Vector Error Correction (VECM) models for the Euro-USD currency (USDEUR) rates using monthly data. The endogenous variables in the VECM specifications are the (log) 1-month forward and spot exchange rates. In the benchmark model ("BM") no exogenous and autoregressive variable is used. In VECM-RV, the exogenous variable is the log of the realized volatility of the previous month (calculated on basis of the sum of squared log spot returns over 5-minute intervals and it is called "OwnRV"). In VECM-BAS, VECM-OF and VECM-PI, three measures of liquidity of the previous month are the exogenous variables. Taking the monthly averages, these are the bid-ask spread ("BAS"), the order flow in absolute value ("ABSOF") and the price impact coefficient ("PI"), which is estimated via regression as the slope coefficient regressing hourly log return on a constant and order flow. The specification called VECM-RV-BAS, -OF as well as –PI includes realized volatility and a liquidity measure at time as exogenous variables. T-statistics and Adjusted R-squared tests are also reported. The sample period spans from December 1996 to February 2008 (the German mark replaced the euro before 1999).

	BM	VECM-RV	VECM-BAS	VECM-OF	VECM-PI	VECM-RV-BAS	VECM-RV-OF	VECM-RV-PI
EC coeff	-4.289	0.230	-0.899	-2.375	0.338	0.448	-1.724	1.029
	-2.346	2.360	-0.642	-1.518	0.315	2.184	-0.985	1.704
OWNRV	-	-1.811				-1.766	-0.975	-1.233
		-2.271				-2.174	-2.018	-1.485
BAS	-	-	16.948			-6.311		
			0.378			-0.118		
ABSOF	-	-		-3.245			-2.572	
				-2.417			-1.922	
PI	-	-			-1.080			-0.865
					-2.114			-1.646
Adj. R-sq.	0.039	0.087	0.016	0.073	0.055	0.073	0.098	0.083