# Money market operations and volatility of UK money market rates

*Anne Vila Wetherilt*

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Bank of England, Threadneedle Street, London, EC2R 8AH. Contact details:
anne.vila-wetherilt@bankofengland.co.uk; tel: 020 7601 4649; fax: 020 7601 5953.

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**Abstract**

In this paper, we examine whether in the United Kingdom the choice of the operational framework for monetary policy has been systematically related to patterns in money market rates. We first focus on the Bank of England's policy target, the two-week repo rate. Our tests indicate that tighter spreads between the two-week market rate and the official repo rate result in lower money market volatility at the very short end of the money market curve. The effects at the longer end are much weaker. But we find no evidence of transmission of two-week volatility along the money market curve. In contrast to many other central banks, the Bank of England does not employ an operating target for the overnight rate. We find no evidence that allowing greater variation in overnight rates undermines efforts of the central bank to keep other money market rates in alignment with the rate at which it operates when implementing its monetary policy.

Our results further indicate that volatility of rates at the very short end of the UK money market yield curve has declined significantly since the early 1990s. The introduction of the gilt repo market in January 1996 was associated with lower money market volatility, although we have evidence that volatility had started to fall as early as mid-1995. The effects of the 1997 reforms of the Bank of England's open market operations are less discernible in the data. In contrast, the creation of a ceiling for overnight rates in June 1998 was more clearly associated with a reduction in volatility of end-of-day overnight rates.

**Summary**

It is widely accepted — both in the central bank and academic communities — that a key objective of a central bank's operational policy is to minimise persistent deviations of the relevant money market rate(s) from its policy rate. First, it is argued that excessive money market volatility might give the market confusing messages about the stance of monetary policy and is therefore to be avoided. Second, it is claimed that such short-term volatility may be transferred up the yield curve, which could affect asset markets and in turn have real economic effects. An important practical question is whether the choice of policy instruments affects this objective.

The past decade has witnessed a multitude of changes in the operational framework for monetary policy across developed countries. In the United Kingdom, important structural changes include the creation of the open gilt repo market in January 1996, the introduction of gilt repo in the Bank of England's daily open market operations in March 1997, and the introduction of a ceiling for overnight rates in July 1998.(1) The present paper examines whether these and other reforms to the Bank's money market operations have been accompanied by significant changes in money market rates and volatility. The paper also offers some guidance on how to measure the effectiveness of operational policy best.

The paper conducts an empirical study, using daily money market rates, ranging from the overnight to twelve-month maturity. We develop an empirical model that captures the key features of the data, in particular the time-varying nature of volatility. Using this framework, we analyse volatility of the key money market rates (the overnight and two-week rate). We then use this model to examine the relationship between short-term money market volatility and spreads. We also examine whether this volatility is transmitted up the money market yield curve to affect longer maturity rates. Furthermore, we assess the speed of adjustment of interest rates along the money market yield curve to changes in official rates. We also investigate whether *not* choosing the overnight rate as a policy target has significant implications for money market volatility.

The research shows some evidence of a statistical relationship between key money market spreads and volatility at the very short end of the money market curve. The evidence is weak though, and does not extend to the longer end of the curve. First, we find no evidence of transmission of two-week volatility along the money market curve. Second, we find no evidence that allowing greater variation in overnight rates undermines efforts of the central bank to keep other money market rates in alignment with its chosen operational monetary policy target. Third, we demonstrate that spreads between the two-week market rate and the official repo rate affect both money market volatility and rate dynamics at the short end of the money market curve. The effects at the longer end are much weaker. In contrast, the overnight spread has little impact on money market rate volatility or dynamics.

Our tests further indicate that volatility of rates at the very short end of the UK money market yield curve has declined significantly since the early 1990s. The introduction of the gilt repo market in January 1996 was associated with lower money market volatility, although we have evidence that volatility had started to fall as early as mid-1995. The effects of the 1997 reforms

(1) The June 2001 introduction of a floor for overnight rates is outside our sample period.

of the Bank of England's open market operations are less discernible in the data. In contrast, the creation of a ceiling for overnight rates in June 1998 was associated with a reduction in volatility in end-of-day overnight rates.

## 1. Introduction

The past decade has witnessed a multitude of changes in the operational framework for monetary policy across developed countries. Most noteworthy are the trend towards reducing or removing reserve requirements, the increased use of repo transactions by central banks and the greater reluctance of central banks to use open market operations for signalling purposes. These reforms have often been associated with lower volatility of money market rates.(2) At the same time, both the central banking and the academic literature have produced theoretical models that demonstrate, albeit in very stylised set-ups, that certain operational arrangements are preferable to others.(3) In these models, the central bank chooses a policy rate and aims to minimise deviations of market rates from the policy rates. The rationale for this objective function is that excessive money market volatility might give the market confusing messages about the stance of monetary policy and is therefore to be avoided. An additional argument is that short-term volatility may be transferred up the yield curve, which would affect asset markets and in turn have real economic effects.

In this paper, we provide an empirical model for the money market rates that are most directly affected by the central bank (in the United Kingdom, these are the two-week rate and the overnight rate). We first employ this model to obtain estimates of (conditional) money market volatility. We then use the model to examine the relationship between short-term money market volatility and spreads. We also examine whether this volatility is transmitted up the money market yield curve to affect longer maturity rates. Third, we assess the speed of adjustment of interest rates along the money market yield curve to changes in official rates. We also investigate whether *not* choosing the overnight rate as a policy target has significant implications for money market volatility.

Finally, we assess whether in the United Kingdom changes in the operational framework for monetary policy have been systematically related to patterns in money market rates. We conduct a number of empirical tests using data from 1994 to 2001. Our sample period covers a number of important operational changes, including the creation of the gilt repo market in January 1996 and the introduction of gilt repo in the Bank of England's daily open market operations in March 1997.

Our main results are the following. First, we find no evidence of transmission of two-week volatility along the money market curve. Second, we find no evidence that allowing greater variation in overnight rates undermines efforts of the central bank to keep other money market rates in alignment with the rate at which it operates when implementing its monetary policy. Third, we demonstrate that spreads between the two-week market rate and the official repo rate affect both money market volatility and rate dynamics at the short end of the money market curve. The effects at the longer end are much weaker. In contrast, the overnight spread has little impact on money market rate volatility or dynamics.

(2) See, for example, Borio (1997).
(3) See, for example, Ayuso and Repullo (2000), Bartolini *et al* (2000a), Davies (1998), and Quirós and Mendizábal (2000).

Our results further indicate that volatility of rates at the very short end of the UK money market yield curve has declined significantly since the early 1990s. The introduction of the gilt repo market in January 1996 was associated with lower money market volatility, although we have evidence that volatility had started to fall as early as mid-1995. The effects of the 1997 reforms of the Bank of England's open market operations are less discernible in the data. In contrast, the creation of a ceiling for overnight rates in June 1998 was more clearly associated with a reduction in volatility in end-of-day overnight rates.

The remainder of the paper is organised as follows. In Section 2, we provide a brief overview of the literature. In Section 3, we describe the Bank of England's operational policy. The data are discussed in Section 4. In Section 5, we explain our modelling framework, namely a single equation component GARCH model (Section 5.1) and a vector error correction model (Section 5.2). We present the results in Section 6, and conclude in Section 7.

## 2. Review of the literature

In this section, we sketch a conceptual framework to assist us in evaluating the effectiveness of the Bank's operational policy. Borio (1997) makes a useful distinction between the *strategic level of monetary policy* and the *tactical level*. The strategic level refers to the process employed by the central bank to determine monetary policy. The tactical level refers to the procedures in place to implement monetary policy. These procedures affect demand and supply in the interbank market for short-term unsecured loans, which forms part of the money market. An important segment of this market is the overnight market, where financial institutions trade in so-called central bank reserve balances. These are deposits held by major financial institutions at the central bank on an overnight basis. Financial institutions use the overnight market to manage the intraday liquidity needs that arise from consumer transactions, and to avoid costly overdrafts on their end-of-day balances with the central bank. As we will see below, it is on this aspect of central bank operational policy that the theoretical literature has mostly focused.

At the tactical level, it is widely accepted that a key objective of the central bank is to minimise deviations of the relevant money market rate(s) from its policy rate.[4] In equilibrium, the money market rate is jointly determined by the central bank and by money market participants' optimising behaviour. In the theoretical literature, some authors model the central bank's objective as a quadratic loss function. Market participants are modelled as weighing the expected opportunity cost of holding money on central bank deposits against the expected cost of overdrafts. The literature shows that their demand is affected by expectations of future money market rates, the existence of reserve requirements and standing facilities (see below) and the credibility enjoyed by the central bank.[5]

Policy rates differ across countries. Some central banks directly target the overnight market by selecting a target level for the overnight rate (for example the United States). Elsewhere, the central bank chooses a different maturity (for example two weeks in the United Kingdom and the

(4) See, for example Allen (2002).
(5) See, for example, Bartolini, Bertola and Prati (2000a), Quirós and Mendizábal (2000), Davies (1998).

euro area) for its policy rate, yet has an interest in ensuring that the behaviour of the overnight rate is consistent with its policy objective.

In order to achieve its objective, the central bank has access to a range of *instruments*, typically organised under three headings: reserve requirements,[6] open market operations and standing facilities (end-of-day lending and deposit facilities). The majority of theoretical work has been concerned with reserve requirements.

In the presence of liquidity shocks to the demand or supply of central bank reserve balances, the central bank can use any of the above instruments to avoid market rates moving too far way from the policy rate. Open market operations directly affect the amount of liquidity in the market, as they shift the supply curve. Reserve requirements affect the slope of the demand curve and as such limit movements in the equilibrium market rate for a given liquidity shock. Standing facilities put a floor and ceiling on the movement of money market rates (typically the overnight rate). Guthrie and Wright (2000) show that open market operations will not be successful, unless the market believes that the central bank is committed to keeping market rates close to its policy rate. If market participants incorporate this belief into their demand, then the market-clearing rate will be close to the policy rate, thereby reducing the need for open market operations.[7]

The theoretical literature offers a number of key results that are useful to design testable hypotheses. First, the central bank's objective function employed in this literature implies that operational policy is more effective when spreads of key money market rates over the policy rates (in the context of the United Kingdom, the overnight and two-week rates) are narrow and stable over time. This motivates us to look at the time-series properties of these money market spreads and their volatility.

Second, the theoretical models suggest that credibility will result in narrower and less volatile spreads, as market participants will be less inclined to trade away from the policy rate. Credibility further implies that should divergences arise, then they can be expected to be short-lived. Hence, we will wish to examine the persistence in both the level and the volatility of these money market rates.

Guthrie and Wright (2000) further show that the expectation of future threats will tie down future money market rates, and via the expectations hypothesis all other future rates. This motivates us to examine the time-series behaviour of the entire spectrum of money market rates. Our

(6) Reserve requirements typically impose an average minimum level on banks' settlement accounts, with the average applying to a so-called maintenance period. It is a widely accepted view that such requirements reduce volatility of the overnight rate and remove the need for very frequent open market operations (see, for example, Davies (1998) and Borio (1997)). In contrast to many other central banks, the Bank of England does not employ reserve averaging. This means that UK settlement banks are not required to hold reserves at the Bank, but have to balance their accounts with the Bank at the end of every working day in order to avoid penalties.

(7) Guthrie and Wright (2000) go a step further and argue that the central banks can use signalling (open mouth operations) to implement monetary policy, rather than having to rely on open market operations. In their model, the central bank chooses a target level for the overnight rate, and subsequently threatens to use open market operations to alter liquidity if market rates diverge too much from the target rate. If the market takes this threat seriously, it will ensure that current rates are where the central bank wants them to be and no actual interventions will be required.

hypothesis is that a more effective operational policy should result in lower volatility of the entire money market curve.

Third, market expectations of future monetary policy decisions are another cause of predictable patterns in money market rates (or spreads) and their volatility. Schnadt and Whittaker (1995) model the borrowing and lending behaviour of market participants in the period preceding a policy decision, when it is expected that official rates will be changed. They demonstrate that predictable patterns in money market rates and their volatility arise when the central bank chooses a longer-maturity policy rate (for example two weeks), while allowing money market participants to operate at shorter maturities (for example overnight).(8) This line of research suggests that money market volatility will display predictable time variation. Our empirical specification (see Section 5.1 below) will incorporate this insight.

Fourth, we would expect the institutional arrangements of a central bank's operational policy to affect the behaviour of money market rates. For example, we would expect the introduction of overnight standing facilities to limit the volatility of the overnight rate within the publicly announced corridor. Likewise, we might expect steps taken to widen the pool of money market participants to result in greater liquidity in the market, and consequently in lower variability of rates. The auction format chosen for the central bank's open market operations is another variable to consider. For example, Nyborg and Strebulaev (2001a) show that fixed-rate auctions (like those employed by the Bank of England as we will explain in the next section) result in lower post-auction rate volatility than variable-price auctions do. Our paper will examine a few of these institutional features in the context of the Bank of England's operational procedures in the 1990s.(9)

## 3. Operational framework

Since 1997, the Bank of England has implemented its monetary policy via the official two-week repo rate.(10) This is the rate at which the Bank conducts repo transactions with its counterparties as part of its open market operations. The official rate is closely tracked by the two-week

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(8) Their argument goes as follows: When market participants expect a rate fall, they will want to borrow from the central bank for the shortest possible period (ie overnight). Short rates up to the two-week maturity will fall, reflecting the fall in demand, thereby anticipating the expected rate cut. When market participants expect official rates to rise, they have an incentive to borrow from the central bank for the longest possible period (ie two weeks) to lock in the prevailing official rate. The resulting fall in demand for very short-term funds (for example overnight) causes very short-term rates to fall prior to the expected rate rise, only to catch up thereafter (referred to as pivoting). Moreover, as the probability of a rate rise increases, short-term volatility rises (more so than when a fall in the policy rate is expected). The authors conclude that the resulting volatility could be avoided by conducting open market operations at the overnight maturity only.

(9) The theoretical literature further demonstrates that in the presence of reserve requirements, money market rates can be characterised by a martingale process during the maintenance period. This property stems from a simple no-arbitrage condition that will hold during the maintenance period (except for the final day), when banks weigh the opportunity cost of excess reserves against the expected penalty of not meeting the requirement, but are indifferent between borrowing money on different days of this period. Importantly, the martingale property implies that anticipated changes in reserve holdings should not cause predictable patterns in interest rates during the maintenance period. In the context of the United Kingdom, however, banks are not subject to reserve requirements, so we will not consider this issue in the present paper.

(10) Much of the material in this section was taken from *The Bank of England's Operations in the Sterling Money Markets* (1997).

market-determined GC repo rate. The Bank's rate is typically higher though; among other possible reasons, market participants appear willing to pay a premium for the more flexible collateral arrangements allowed by Bank repo (Brooke and Cooper (2000)). The 1997 reforms also widened the range of counterparties that are able to participate in the Bank's auctions. They include a wide range of financial institutions that are active in the sterling money markets.

The adoption of the two-week repo rate as the target for monetary policy followed on the heels of the January 1996 gilt repo reforms. While gilt repo arrangements had been available since the early 1990s, their use was relatively restrictive.(11) The 1996 reforms removed these restrictions on participation and allowed for the development of a liquid gilt repo market. Consequently, the amounts outstanding in the gilt repo market expanded from £72 billion in 1997 to £128 billion at the end of 2000.

The Bank conducts its open market operations using a range of short-term money market instruments. These include repo of gilts and eligible bills (Treasury bills and eligible local authority and bank bills), and outright purchase of eligible bills. The maturity of the Bank's open market operations is principally at two weeks, with minor variations, depending on liquidity needs.(12) The pool of securities eligible for use in the Bank's open market operations has been extended since 1997, most notably in August 1999, when euro-denominated securities issued by governments and central banks in the European Economic Association were added to the list. Table A provides a breakdown of the Bank's open market operations by instrument type.

**Table A: Bank of England money market operations (1997-2001)**

| % of total | 1997 | 1998 | 1999 | 2000 | 2001 H1 |
|---|---|---|---|---|---|
| Gilt repo | 63.6 | 64.2 | 71.1 | 64.3 | 63.2 |
| Overnight gilt repo | 0.8 | 1.2 | 1.5 | 2.2 | 3.7 |
| Bill repo | 21.8 | 21.8 | 14.4 | 12.0 | 8.9 |
| Euro repo | - | - | 2.2 | 16.5 | 20.4 |
| Outright purchases | 13.7 | 12.7 | 10.7 | 3.9 | 3.7 |

Source: Bank of England.

Prior to 1997, open market operations were mainly conducted via outright purchases or sales of eligible bank bills and sterling Treasury bills. A key rate was the so-called minimum Band 1 dealing rate, the minimum rate at which the Bank was willing to discount bills with up to 14 days maturity. As a reaction to the September 1992 ERM crisis, the Bank introduced repo facilities of gilts and loans related to export and shipbuilding credit. These were re-offered on a number of occasions thereafter, and from April 1994 became a permanent part of the Bank's open market operations. They were conducted twice a month with a maturity of generally two or four weeks.

From 1997 to 1998, there were two daily rounds where the Bank's counterparties could bid for two-week repo or outright sales (12:00 noon and 2:30 pm), and sometimes an additional early

(11) Gilt repo was available to a limited group of market participants only, at fixed fees, and could only be used to cover short positions.
(12) Between October 1999 and February 2000, the Bank offered repos with up to three-month maturity to assist in managing liquidity needs over the millennium date change.

round (9:45 am) depending on liquidity conditions. In June 1998, this was modified to two regular daily rounds (9:45 am and 2:30 pm) for two-week repo and outright sales. In addition, two end-of-day facilities were created for overnight repo. At 3:30 pm, all counterparties can bid for additional funds at a penal rate (currently 100 basis points above the Bank's repo rate). As such, the Bank introduced a ceiling for the overnight rate.(13) After the close of the money markets, the 4:20 pm facility allows settlement banks to obtain additional funds (at a penal rate of 150 basis points above the official rate) that might be needed in order to balance their account with the Bank at the end of the day.(14) In June 2001, the Bank of England introduced an overnight deposit facility (remunerated at 100 basis points below the Bank's repo rate). This facility is made available to the Bank's counterparties at 3:30 pm. This policy change, however, falls outside the sample period considered in this paper.

## 4. Data and stylised facts

Our empirical tests employ daily interbank data on UK money market rates for the period 1/4/1994 to 26/6/2001. With 33% of the total amount outstanding (June 2001), the interbank market forms the largest segment of the sterling money markets.(15) We employ Datastream LIBOR rates for overnight, one-week, and one, three, six, and twelve-month rates. These are end-of-day rates obtained by FTSE International from a sample of market participants. Two-week rates were available from the Bank of England. They are the best offer rates available at 8:30 am.(16) The total sample contains 1,891 observations.

**Table B: Summary statistics (1994-2001)**

| Repo spread (%) | Overnight | 1-week | 2-week | 1-month | 3-month | 6-month | 12-month |
|---|---|---|---|---|---|---|---|
| Mean | -0.35 | -0.17 | -0.04 | -0.05 | 0.10 | 0.21 | 0.42 |
| Median | -0.28 | -0.09 | 0.00 | -0.03 | 0.12 | 0.22 | 0.44 |
| Stand. dev | 0.80 | 0.29 | 0.21 | 0.16 | 0.20 | 0.32 | 0.54 |
| Min | -3.44 | -2.00 | -1.25 | -0.81 | -0.38 | -0.63 | -0.91 |
| Max | 6.25 | 0.57 | 0.44 | 0.31 | 0.81 | 1.19 | 1.94 |
| Persistence | 0.26 | 0.85 | 0.90 | 0.93 | 0.96 | 0.98 | 0.99 |

The charts and summary statistics (Table B) for spreads of the various rates over the two-week repo rate reveal a number of interesting patterns. First, spreads for maturities one month and beyond behaved similarly during most of the sample period, in that they saw periods of high volatility, followed by periods of much lower volatility. Close inspection of the charts also shows that one and two-week spreads have similar volatility profiles, which are lower than some of the longer maturities. But, the overnight spread looks very different, with higher volatility and

(13) Prior to June 1998, only a limited number of market participants had access to a late lending facility and their borrowing capacity was limited by quotas. Hence, the late lending rate did not effectively cap the overnight rate.
(14) In both the 3:30 pm and the 4:20 pm rounds, overnight funds can be obtained at the normal repo rate if the liquidity needs resulted from late changes to the Bank of England's daily liquidity forecast.
(15) This proportion declines over the sample period. For example in June 1997, the interbank market accounted for 39%. Certificates of deposit form the second largest category, with 24% in June 2001 (25% in June 1997), closely followed by gilt repo, with 24% in May 2001 (22% in May 1997). Source: Bank of England.
(16) We compared the Datastream one-week rate with the one-week rate obtained from the same data source as the two-week rate. For the sample period as a whole, we found the correlation coefficient to be 0.99.

much lower persistence. Second, Table B reveals a U-shaped pattern in the standard deviation of spreads, with the minimum at one month. Beyond one month, spread volatility increases with maturity, but spread persistence increases as well.

These preliminary statistics illustrate that money market rates and their spreads over the policy rate have time-varying variability, suggesting that a GARCH model would be suitable. Standard unit root tests reject the null hypothesis of a unit root (non-stationarity) for all, but the twelve-month spread (see Table C). In line with the literature (see for example Hall, Anderson and Granger (1992)), we cannot reject the null hypothesis for the levels of rates beyond one week, but do so for the first differences.[17] This suggests that money market rates are best modelled as I(1) processes.[18] Consequently, our empirical model needs to be specified in terms of first differences.

**Table C: Unit root tests (1994-2001)**

| **Rates** | Overnight | 1-week | 2-week | 1-month | 3-month | 6-month | 12-month |
|---|---|---|---|---|---|---|---|
| ADF-test statistic* | -13.95 | -4.08 | -2.42 | -1.49 | -1.21 | -1.18 | -1.38 |
| **First diff of rates** | | | | | | | |
| ADF-test statistic* | -49.22 | -39.45 | -37.99 | -34.22 | -33.39 | -33.64 | -32.61 |
| **Repo spread** | | | | | | | |
| ADF-test statistic* | -21.49 | -10.94 | -8.22 | -6.99 | -5.55 | -3.54 | -2.37 |

*Test carried out with intercept and one lag. 5% (1%) critical value is –2.86 (-3.43).

While money market rates may be non-stationary, it is still possible to find one or more linear combinations of the series that are stationary. In this case, the series themselves are said to be cointegrated, and the stationary linear combination(s) is (are) referred to as the cointegrating equation(s) and represents a long-run equilibrium relationship. Following a common shock, cointegrated series gradually converge to their long-run equilibrium relationship(s).

Hall, Anderson and Granger (1992) consider US Treasury bill yields of different maturities and show that any yield series is cointegrated with the shortest maturity yield (in their model, the one-month T-bill yield).[19] Hence, it follows that one can choose the $n$-1 spreads over the one-month yield as cointegrating vectors. They then show that any of the $n$ yield series can be used to construct the cointegrating vectors, since the spread between any two yields can always

(17) Perron (1990) shows that in the presence of regime shifts, unit root tests will be biased towards not rejecting the null hypothesis.

(18) This is a well-accepted modelling device, even though strictly speaking, (nominal) interest rate series must have finite variances and are bounded below by zero (see for example Hall *et al* (1992)).

(19) This follows from a simple term structure model, where the difference between the $n$-period yield and the one-period yield is equal to the discounted sum of future expected changes in the one-period yield plus a premium. If the right-hand side of this equation is stationary (which implies assuming that the premium is, since the yield changes are stationary), then the left-hand side (the yield spread) is as well. Since this applies to all $n$ yields, it follows that we have $n$-1 cointegrating vectors.

be expressed as the linear combination of two spreads over the one-month yield. We use this line of argument to explore whether UK money market rates can be expressed as stationary linear combinations of the two-week repo rate.

To do so, we carry out the Johanssen cointegration test for the seven UK money market rates and the repo rate ($n$=8). The null hypothesis that the rank of the cointegrating space is no more than 7 ($n$-1) cannot be rejected (see Table D panel 1).[20] Hence, we can proceed on the hypothesis that there are seven cointegrating equations in the form of the spreads of the seven money market rates over the repo rate. This finding motivates the use of a vector error correction model (VECM) in Section 5.2. The seven cointegrating vectors are shown in panel 2 of Table D. They are normalised on the repo rate. While the coefficients of the cointegrating vectors are close to unity, standard likelihood ratio tests reject the hypothesis that they are equal to unity. This is a well-known empirical fact (see for example Sarno and Thornton (2000)). Most authors interpret this result as a rejection of the simple expectations hypothesis, and attribute it to the presence of time-varying risk premia. They continue, however, to assume that a long-term cointegration relationship exists between interest rates of various maturities. In what follows, we will adopt this view.[21]

**Table D: Johansen cointegration tests (1994-2001)**

**Panel 1: Johansen test statistics**

| Null hypothesis: cointegration rank $r$ | Likelihood ratio[a] | Critical values (95%) |
|---|---|---|
| $r = 0$ | 1736.37 | 141.20 |
| $r \leq 1$ | 1111.09 | 109.99 |
| $r \leq 2$ | 649.17 | 82.49 |
| $r \leq 3$ | 416.09 | 59.46 |
| $r \leq 4$ | 220.19 | 39.89 |
| $r \leq 5$ | 97.07 | 24.31 |
| $r \leq 6$ | 28.07 | 12.53 |
| $r \leq 7$ | 0.22 | 3.84 |

[a] Based on Johansen trace statistic. The test procedure consists of estimating a VAR together with a linear combination of the $n$-1 spreads. The test determines the rank of the cointegrating space (the number of cointegrating vectors) together with coefficient estimates for the cointegrating equation(s). We present results for a VAR, which employs 1 lag.

**Panel 2: Cointegrating vectors[b]**

| **Rates** | Overnight | 1-week | 2-week | 1-month | 3-month | 6-month | 12-month |
|---|---|---|---|---|---|---|---|
| Coefficient estimates (st. errors) | -0.94 (0.007) | -0.97 (0.006) | -0.99 (0.005) | -0.99 (0.004) | -1.01 (0.004) | -1.03 (0.006) | -1.06 (0.01) |

[b] Estimates of the vectors (1, $\beta$) for each of the seven cointegrating equations (expressed as a spread over the repo rate). Standard errors are given in parenthesis.

[20] Dale (1993) finds similar results for the period 1987-91.

[21] Since we have $n$ yield variables, and $n$-1 cointegrating vectors of the form (1,-1,0,0,0,0,0,0), we essentially impose ($n$-1)*($n$-2) zero restrictions, in addition to the unit restriction.

## 5. Empirical methods

In this section, we describe the two approaches taken in this paper to model the behaviour of money market rates. First, we model the dynamic behaviour of overnight and other short-term rates using a single-equation approach that allows us to closely examine patterns in money market rate volatility (Section 5.1). Second, we analyse the dynamic interactions between the entire spectrum of short-term rates in a VECM (Section 5.2). Before doing so, we briefly review the existing empirical literature.

While a number of papers have documented the volatility of money market rates, they do so mostly in the context of reserve requirements. Starting with Hamilton (1996), most authors model money market rates as a GARCH model, but allow for the peaks observed in volatility at the end of a maintenance period.[22] Hamilton further suggests that US federal funds rates are characterised by asymmetric responses of volatility to interest rate shocks (rising more following negative shocks), and therefore best described by an E-GARCH model. They also document significant outliers in the data, related to calendar effects, primarily due to end-of-year demand by corporations for short-term credit. Prati *et al* (2001) estimate an E-GARCH model for all G7 overnight rates. They find overnight volatility to be highly persistent and to exhibit many large outliers.

Panigirtzoglou, Proudman and Spicer (2000) focus on the volatility and persistence of the deviations of money market rates from policy rates in countries with (Italy and Germany) and without reserve requirements (United Kingdom). They test both a GARCH (United Kingdom and Italy) and a so-called levels (Germany) specification, the latter modelling volatility as a function of interest rate levels, rather than past volatility or past shocks. They show that overnight rates were more volatile in the United Kingdom than in the other two countries, but rates at slightly longer maturities were not. They further find that deviations of the overnight rate from the policy rate are not statistically significant across the three countries, and that in all three countries persistence of these deviations declines with maturity. Finally, they show that there was a significant reduction in the volatility of UK overnight rates after 1996, which they associate with the introduction of the gilt repo market.

The potential implications of increased money market volatility are considered in Ayuso, Haldane and Restoy (1997). Again modelling money market volatility as a GARCH process, they include a measure of the conditional volatility of the overnight rate in the variance equations for maturities up to one year. They find evidence of transmission of volatility along the yield curve in countries both with (France, Germany and Spain) and without reserve requirements (United Kingdom) for the period 1988-93. They further show that while overnight volatility in the United Kingdom is higher, a smaller proportion is transmitted than in the other countries. In the present paper, we follow the approach taken by Ayuso *et al* (1997), but propose a modified form for the GARCH process.

[22] See, for example, Bartolini *et al* (2000b).

### *5.1 A single equation GARCH model*

Our single equation model has the following form:

$$\Delta r_t^j = \alpha + \sum_{i=1}^{m} \beta_i \Delta r_{t-i}^j + \sum_{i=0}^{n} \gamma_i \Delta o_{t-i} + \delta (r_{t-1}^j - o_{t-1}) + \sum_{s=1}^{S} \lambda_s d_s + \varepsilon_t^j \quad \textbf{(1)}$$

$$\varepsilon_t^j \sim (0, h_t^j) \quad \textbf{(2)}$$

where $j$ refers to the maturity (overnight to one year).

Equation **(1)** models the change in rates $\Delta r_t$ as an autoregressive process, with the $\beta$ coefficients measuring the persistence of rate changes. We also include several lags of changes in the policy rate to measure the reaction of short-term rates to changes of the policy rate $o_t$. We further augment the mean equation **(1)** by an error-correction term ($r_{t-1} - o_{t-1}$), capturing the adjustment of short-term rates to long-run divergences between the short rate and the policy rate. Consistent with discussion in Section 4, this cointegrating equation implies a unit relationship between money market and official rates. Finally, dummies $d_s$ are included to account for calendar effects (namely bank holidays and the end of the calendar year) that are known to produce outliers.(23)

The residuals of the mean equation are modelled as a GARCH process, thereby allowing for autocorrelation and heteroskedasticity. The most general GARCH ($p,q$) process looks as follows:

$$h_t^j = \omega_0 + \sum_{i=1}^{p} \omega_i {\varepsilon_{t-1}^j}^2 + \sum_{i=1}^{q} \phi_i h_{t-i}^j + \sum_{k=1}^{K} \kappa_k d_k \quad \textbf{(3)}$$

This specification captures persistence in volatility (measured by the $\omega$ and $\phi$ coefficients). In each period, the unconditional variance $\omega_0$ is augmented by the estimated variance from earlier periods ($h_{t-i}$) and information about volatility observed in earlier periods (the squared residuals). The higher the coefficients $\omega$ and $\phi$, the longer-lived the effect of past shocks on volatility. Hence, the GARCH model can explain prolonged periods of high (or low) volatility.

Empirical evidence suggests that the time-varying volatility of many financial series is in fact a non-stationary process.(24) Initial estimates of our series indicate that this is indeed the case, with $\omega_1 + \phi_1$ being very close to unity. It follows that the conditional volatility can be characterised by a stochastic trend, with short-term deviations around this trend. To capture these dynamics, Engle and Lee (1999) propose decomposing the conditional variance into a permanent component (trend) and a transitory component, which is mean-reverting to the permanent component.

To do so, they first consider a GARCH (1,1) model and rewrite **(3)**, using the fact that the unconditional volatility $\sigma^2$ is equal to $\omega_0 / (1 - \omega_1 - \phi_1)$:

(23) In common with recent papers (for example Prati *et al* (2001)), we employ dummies for business days on which the money market was closed (bank holidays). We also include a dummy for the day before a bank holiday other than 1 January and a separate dummy for the day before and the day after the year-end. In addition, we employ a dummy to capture the millennium effect (24 December 1999 – 4 January 2000).

(24) See for example Bollerslev, Engle and Nelson (1994).

$$h_t = (1-\omega_1-\phi_1)\sigma^2 + \omega_1\varepsilon_{t-1}^2 + \phi_1 h_{t-1} \quad = \quad \sigma^2 + \omega_1(\varepsilon_{t-1}^2 - \sigma^2) + \phi_1(h_{t-1} - \sigma^2) \qquad \textbf{(4)}$$

(where for the time being we dropped the superscript $j$). Equation **(4)** shows mean reversion to a constant $\sigma^2$. In the component GARCH (C-GARCH) model, this constant volatility is replaced by a time-varying long-run volatility. The C-GARCH model consists of two equations, one describing the conditional variance as before, and one describing the long-run component:

$$h_t = q_t + \omega_1(\varepsilon_{t-1}^2 - q_{t-1}) + \phi_1(h_{t-1} - q_{t-1}) \qquad \textbf{(5a)}$$

$$q_t = \omega_0 + \rho q_{t-1} + \tau(\varepsilon_{t-1}^2 - q_{t-1}) \qquad \textbf{(5b)}$$

The difference between the conditional variance and the trend ($h_t$-$q_t$) is the transitory component of the conditional variance (equation **(5a)**). The persistence of the transitional component is, as in the standard GARCH (1,1), given by $\omega_1 + \phi_1$, and describes how much and how long the conditional variance deviates from its trend. Equation **(5b)** shows that the trend will converge to $\omega_0$ at a rate $\rho$. If $\rho > \omega_1 + \phi_1$, then the transitory component will decay faster than the trend. Combining equations **(5a)** and **(5b)** one can easily show that the C-GARCH is equivalent to a GARCH (2,2) process, and that it reduces to the much used GARCH (1,1) if $\omega_1 = \phi_1 = 0$ or $\rho = \tau = 0$. Engle and Lee (1999) argue that C-GARCH models provide a better insight into the dynamic structure of the conditional variance.

As before, dummies are used to account for outliers in the data that are related to seasonal regularities. Dummies can be inserted into either equation, depending on whether the calendar effect is believed to affect the trend or the deviations from the trend. The fitted value of equation **(5a)** is used as our (conditional) volatility estimate.

### *5.2 A VECM approach*

In Section 4, we established that a cointegrating space of rank $n$-1 exists. It follows that we can construct a vector error correction model (VECM) for UK money market rates where the $n$-1 cointegration equations act as error-correction terms. As indicated above, we choose the $n$-1 vectors to be the spreads over the repo rate. The VECM representation is given by:

$$\Delta R_t = A + B\Delta R_{t-1} + \Phi(R_{t-1} - O_{t-1}) + \Lambda D + \mathrm{E}_t \qquad \textbf{(6)}$$

where $\Delta R_t$ is the vector of seven money market rates plus the repo rate, ($R_{t-1} - O_{t-1}$) the vector of $n$-1 money market spreads that serve as cointegrating equations, $D_t$ a vector of dummies (as before capturing calendar effects) and $E_t$ the vector of residuals. The $j$-th row of the VECM looks as follows ($j$=1..8):

$$\Delta r_t^j = \alpha^j + \sum_{j=1}^{8} \sum_{i=1}^{m} \beta_i^j \Delta r_{t-1}^j + \sum_{n=1}^{7} \delta_n^j (r_{t-1}^n - o_{t-1}) + \sum_{s=1}^{S} \lambda_s d_s + \varepsilon_t^j \qquad \textbf{(7)}$$

From equation **(7)**, we see that the VECM allows us to assess the short-term dynamics of money market rates ($\beta$). In addition, we can measure adjustment over time of the respective rates to deviations of the entire term structure of money market rates from the policy rate (the $\delta^j$ coefficients). It should be noted, however, that the VECM measures the dynamics of rate changes (and can as such be used to quantify lead-lag relationships), but does not provide any guidance on causality.

## 6. Results

### *6.1 Patterns in money market rates*

#### *6.1.1 Overnight rates*

Table E presents the estimation results for the overnight rate. During our sample period, a one percentage point official interest rate change results on average in a 0.86% change in the overnight rate. Any remaining divergence of market rates from the official rate is rapidly corrected, as indicated by the relatively high $\delta$ coefficient of the error-correction term ($\delta$=-0.49). The significance of $\delta$ is also evidence that a long-run cointegration relationship exists between the overnight rate and the policy rate. There is some further short-term persistence in the overnight rate, as indicated by the $\beta$ coefficients, which are significant up to the fourth lag. The variance equation indicates high persistence in the long-term component ($\rho$=0.98), whereas deviations from this trend are slightly shorter-lived ($\omega_1 + \phi_1$=0.73). The very low ARCH-LM test suggests that there are no remaining ARCH effects in the residuals. All calendar dummies (not reported) are significant.

**Table E: C-GARCH estimation results for Libor overnight rate (1994–2001)**

| Mean equation | | Variance equation | | Diagnostics | |
|---|---|---|---|---|---|
| $\gamma_0$ | 0.86 | $\rho$ | 0.98 | N | 1888 |
| | (1.70) | | (418) | $R^2$ | 0.43 |
| $\beta_1$ | -0.32 | $\omega_1$ | 0.01 | ARCH-LM | 0.17 |
| | (-9.13) | | (1.19) | $h_t$ | 0.55 |
| $\beta_2$ | -0.17 | $\phi_1$ | 0.72 | | |
| | (-5.03) | | (9.73) | | |
| $\beta_3$ | -0.10 | $\tau$ | 0.06 | | |
| | (-3.28) | | (7.25) | | |
| $\beta_4$ | -0.05 | | | | |
| | (-2.29) | | | | |
| $\delta$ | -0.49 | | | | |
| | (-14.04) | | | | |

N refers to number of observations, t-statistics in parenthesis, the ARCH-LM test is a Lagrange multiplier statistic to test for any remaining autocorrelation and heteroskedasticity in the residuals. It is asymptotically distributed as a $\chi^2$ ($q$) statistic where $q$ refers to the number of lags specified. We report $q$=1.

*6.1.2 Other maturities*

Table F presents the C-GARCH estimation results for the remaining money market rates up to the twelve-month maturity.

**Table F: Estimation results for short-term rates (1994-2001)**

| | 1-week | 2-week [(a)] | 1-month | 3-month | 6-month | 12-month |
|---|---|---|---|---|---|---|
| $\gamma_0$ | 0.72 | 0.50 | 0.28 | 0.18 | 0.12 | 0.13 |
| | (11.68) | (17.23) | (12.87) | (10.57) | (5.77) | (5.40) |
| $\delta$ | -0.10 | -0.07 | -0.02 | -0.005 | 0.006 | 0.003 |
| | (-11.70) | (-12.15) | (-5.47) | (-1.18) | (1.84) | (1.99) |
| $\rho$ | 0.61 | 0.39 | 0.25 | 0.25 | 0.24 | 0.25 |
| | (22.59) | (5.11) | (10.99) | (5.47) | (1.00) | (16.94) |
| $\omega_1$ | 0.10 | 0.05 | 0.04 | 0.06 | 0.06 | 0.06 |
| | (13.08) | (2.41) | (1.07) | (1.56) | (0.55) | (2.33) |
| $\phi_1$ | 0.04 | 0.01 | 0.02 | 0.006 | 0.02 | 0.001 |
| | (0.70) | (0.30) | (0.48) | (0.15) | (0.17) | (0.03) |
| $\tau$ | 0.12 | 0.10 | 0.05 | 0.08 | 0.06 | 0.07 |
| | (6.76) | (5.11) | (1.49) | (2.12) | (0.60) | (3.73) |
| $R^2$ | 0.15 | 0.11 | 0.08 | 0.09 | 0.05 | 0.15 |
| ARCH-LM | 0.17 | 0.61 | 0.20 | 4.79 | 3.83 | 1.65 |
| $h_t$ | 0.02 | 0.007 | 0.003 | 0.002 | 0.002 | 0.003 |

(t-statistics in parenthesis, the $\beta$ coefficients are not reported.)

(a) The $\gamma_0$ coefficient is set equal to 0 in the two-week equation, instead the estimate of $\gamma_1$ is reported. This takes into account the time difference between the two-week rate (recorded at 8:30 am) and the remaining rates (daily close).

The results illustrate how the impact of changes in the official rate declines with maturity (the coefficient $\gamma_0$ falls, but remains significant), as does the rate of adjustment to temporary discrepancies from the official rate ($\delta$ falls and ceases to be significant). The variance equations show a significant fall in the persistence of the long-term trend (from 0.61 for the one-week rate to 0.25 for all rates beyond one month). Together with a decrease in deviations from the trend ($\omega_1 + \phi_1$ falls from 0.14 for the one-week rate to 0.09 for the twelve-month rate), this results in a substantial fall in the conditional volatility ($h_t$ = 0.02 for the one-week rate and below 0.01 for all remaining maturities). Table F further shows that while the $\rho$ coefficient is significant for all but the six-month maturity, the coefficients of the transitory components cease to be significant beyond two weeks. The ARCH-LM statistics, while still below the relevant $\chi^2$ values, are higher for some of the longer maturities (three and six months in particular). These results suggest that the C-GARCH model is most useful at the very short end of the yield curve, as it allows us to separate the trend component from short-term deviations that most likely are related to non-economic factors.

### *6.2 The relationship between overnight rates, two-week rates and the remainder of the money market yield curve*

In this section, we use the C-GARCH framework to look for evidence of volatility transmission along the money market yield curve. We focus on the impact of the two-week and the overnight rate. In doing so, we take the view that since these are the rates that are most directly influenced by the Bank of England's open market operations, their volatility constitutes a useful measure of the effectiveness of its operational policy.

#### *6.2.1 The effect of higher volatility*

First, we follow Ayuso *et al* (1997) and include our measure of conditional volatility for the overnight rate into equation **(5a)**:

$$h_t^j = q_t^j + \omega_1(\varepsilon_{t-1}^{j^2} - q_{t-1}^j) + \phi_1(h_{t-1}^j - q_{t-1}^j) + \pi h_t^{on} \qquad \textbf{(8)}$$

Equation **(8)** is estimated for all maturities of one week and beyond. The coefficient $\pi$ measures the proportion of overnight volatility that is transmitted to the longer maturity through deviations from the trend. Alternatively, one could measure volatility transmission through the trend itself and include overnight volatility in the trend equation **(5b)**. In the present paper, we present the results for the transitory equation only, but the results for the trend equation are generally very similar.[25] Second, we use the above framework to assess the impact of two-week volatility on money market rates (replacing $h^{on}$ by $h^{2w}$).

**Table G: Volatility transmission: C-GARCH estimation results for Libor overnight and two-week rates (1994-2001)**

| **Impact on volatility of:** | **Overnight volatility** | **2-week volatility** |
|---|---|---|
| Overnight rate | - | 6.0 (1.60) |
| 1 week | 0.06 (0.51) | 0.40 (2.15) |
| 2 weeks | 0.01 (0.76) | - |
| 1 month | 0.001 (0.16) | 0.01 (0.70) |
| 3 months | 0.0001 (0.45) | 0.003 (0.96) |
| 6 months | -0.00001 (0.003) | -0.002 (-0.13) |
| 12 months | -0.003 (-0.76) | 0.01 (0.96) |

(t-statistics in parenthesis.)

As the first column of Table G shows, the $\pi$ coefficients that measure the impact of overnight volatility are generally positive, but never statistically significant. Volatility of the two-week rate (shown in the second column of Table G) is slightly more important. It has a positive effect on money market volatility at most maturities, but is significant only at the one-week maturity,[26] and again rapidly declining beyond two weeks.

[25] A full set of results is available from the author. Where significant differences arise, we will note so in the text.
[26] This significance result is highly unstable, in that it frequently vanishes when dummies are added or removed, and does not appear when inserting two-week volatility in the permanent component.

### *6.2.2 The effect of wider spreads*

If central banks implement policy in such a way that market rates are kept close to policy rates, then the effectiveness of monetary policy can also be gauged from the time-series patterns of those spreads. Moreover, spreads and rate volatility could be viewed as complementary measures. Indeed, at times high volatility in overnight or two-week rates could be a reflection of market uncertainty (for example shortly before a policy meeting), rather than the result of reduced operational effectiveness. At other times, active intervention to keep rates from departing from the policy rate might be translated into higher rate volatility. In these circumstances, rate volatility alone would not present an accurate assessment of operational effectiveness. For these reasons, we will not only wish to examine the behaviour of spreads over time, but also their impact on volatility of longer-date market rates. To do so, we re-estimate the C-GARCH model, but now include a (squared) spread term in the volatility equation:

$$h_t^j = q_t^j + \omega_1(\varepsilon_{t-1}^{j^2} - q_{t-1}^j) + \phi_1(h_{t-1}^j - q_{t-1}^j) + \varsigma(r_t^{on} - o_t)^2 \qquad \textbf{(9)}$$

Equation **(9)** allows us to examine whether wider spreads between the overnight rate and the policy rate have an additional effect on short-term rate volatility. We then repeat this exercise for the spread between the two-week market rate and the repo rate (replacing $r^{on}$ by $r^{2w}$). Table H presents the results.

**Table H: The effect of deviations from the repo rate on money market volatility: C-GARCH estimation results for Libor overnight and two-week rates (1994-2001)**

| **Impact on volatility of:** | **Overnight - repo** | **2-week - repo** |
|---|---|---|
| Overnight rate | - | 0.3 (6.73) |
| 1 week | 0.002 (5.31) | 0.06 (8.32) |
| 2 weeks | 0.0003 (2.86) | - |
| 1 month | 0.0001 (4.97) | 0.009 (7.75) |
| 3 months | -7.8 $10^{-6}$ (1.77) | -5.9 $10^{-5}$ (1.45) |
| 6 months | -2.9 $10^{-5}$ (1.57) | 0.0002 (0.69) |
| 12 months | 4.6 $10^{-7}$ (0.21) | 3.3 $10^{-5}$ (0.54) |

(t-statistics in parenthesis.)

Our results indicate that money market volatility up to one month is significantly higher when the Libor overnight rate is further away from the official repo rate (column 1 of Table H). Likewise, volatility up to one month is significantly affected by a wider two-week spread (column 2 of Table H). Beyond one month, these spreads have no significant impact.(27)

Comparing the results in Tables G and Table H, we see that volatility at the very short end of the money market curve is more sensitive to wider spreads over the official repo rate than to either overnight or two-week volatility increases. Hence, we might conclude that the beneficial effects

(27) In a slightly different statistical model, Panigirtzoglou *et al* (2000) find that overnight, one-week and one-month volatility are not significantly affected by their respective spreads with the repo rate (lagged one period).

of keeping spreads narrow are greater than those that stem from direct efforts to reduce rate volatility.

### *6.3 Volatility transmission and institutional reforms*

To assess whether the various changes in the UK operational framework of the 1990s did affect patterns in UK money market rates, we next re-estimate the C-GARCH model for selected subperiods. Specifically, we consider the introduction of the UK repo market (January 1996), the adoption of repo transactions by the Bank of England for its daily open market operations (March 1997), the modifications to the daily rounds with the introduction of the ceiling for the overnight rate (June 1998) and the expansion of the pool of eligible collateral (August 1999).

Each new subperiod starts on the day of the reform.(28) We first re-estimate the C-GARCH model for overnight and two-week rates. We subsequently re-estimate the transmission equations, using the new estimates for overnight and two-week volatility in equation **(8)**, and (as before) the repo spreads in equation **(9)**. Hence, we are able to document whether the reforms i) produced a shift in the conditional volatility and ii) affected the transmission of volatility up the money market curve. Table I below summarises some of our results. The complete tables are given in the appendix.

#### *6.3.1 Overnight and two-week rates and spreads (subperiods)*

Chart 2 shows that the conditional volatility of the overnight rate (as estimated by the C-GARCH equation **(5a)**) has fallen throughout the 1990s, with the exception of a short-lived peak in the fourth quarter of 1997 and the first quarter of 1998. Overnight volatility declined in 1994 and 1995 as a result of a combination of technical (balance sheet) factors and policy considerations (post-Barings).(29) So at first sight, the January 1996 reforms do not seem to have had any clear volatility-reducing effect. Technical factors further contributed to heightened money market volatility in the final quarter of 1997.(30) Some of this volatility may also have been related to the gradual phasing out of transitional arrangements that had been in place since the March 1997 reforms.(31) Finally, Chart 2 reveals a clear break in the series, with high and strongly mean-reverting volatility up to the middle of 1998 and much lower and slower-moving volatility thereafter. This could indicate that the late-round lending facility introduced in July 1998 has been effective at constraining overnight volatility.

(28) Alternatively, one can insert dummies corresponding to the different subperiods into equations **(5a)** or **(5b)**. These dummies take on the value one on the day of the reform and thereafter, and are zero beforehand. The method employed in the text provides more flexibility as it allows us to obtain subperiod estimates for all the variables of the mean and variance equations. For completeness, we will consider both approaches.
(29) The early 1990s were characterised by high variability in both government and private sector borrowing, which had an adverse impact on liquidity in the money markets. Together with the consequences of the ERM crisis, this led to high rate volatility. See 'Market operations since September 1992', *Bank of England Quarterly Bulletin*, February 1995, pages 12-13.
(30) This volatility increase was attributed to large daily shortages (linked to gilt sales and government spending) which in turn led to higher than normal use of the late-day lending facility. *Bank of England Quarterly Bulletin*, February 1998, pages 11-12, and May 1998, pages 109-11. Until June 1998, this facility was restricted to a small group of market participants (see above), and as such did not constitute an effective ceiling for the overnight rate.
(31) 'Sterling wholesale markets: developments in 1998', *Bank of England Quarterly Bulletin*, February 1999, pages 33-39.

Chart 3 shows that two-week volatility was characterised by a marked break mid-1995, as the conditional volatility fell and became less volatile itself. This decline followed a period of relatively high volatility during 1992 and 1993. By early 1994, two-week volatility had fallen markedly, yet the market continued to experience peaks of high volatility, as can be seen from Chart 3. These occurred at the end of 1994, and again in early 1995, when in the wake of the Barings crisis, the Bank had been willing to allow slightly larger deviations between the two-week rate and the policy rate. By late 1995 the Bank decided to return to a less accommodative operational policy. Spreads narrowed (see Chart 1C) and rate volatility declined as a result.[32] It was as such unrelated to any structural changes. Chart 3 further shows that two-week rate volatility was relatively low and stable from early 1996 to late 1999, except maybe for a small and short-lived peak in late 1998. After 1999, two-week volatility rate increased slightly and became more persistent as well. Some, but not all, of this rise could be attributed to end-of-year effects, in particular the millennium changeover.

To assess whether overnight and two-week rate volatility were significantly affected by the various reforms, we re-estimate the GARCH model for each of the subperiods. The results are presented in Table I.

**Table I: Estimation results for overnight and two-week rates (subperiods)**

| **Panel 1: Overnight rate** | | | | | |
|---|---|---|---|---|---|
| | 1994-96 | 1996-97 | 1997-98 | 1998-99 | 1999-2001 |
| $\rho$ | 0.77* | 0.93* | 0.98* | 0.90* | 0.96* |
| $\omega_1 + \phi_1$ | -0.09 | 0.12 | -0.80 | 0.29 | 0.14 |
| $h_t$ | 0.69 | 0.40 | 0.85 | 0.42 | 0.25 |
| **Panel 2: Two-week rate** | | | | | |
| | 1994-96 | 1996-97 | 1997-98 | 1998-99 | 1999-2001 |
| $\rho$ | 0.58* | 0.26 | 0.24 | 0.24 | 0.49* |
| $\omega_1 + \phi_1$ | 0.05 | -0.01 | 0.07 | 0.10 | -0.19 |
| $h_t$ | 0.014 | 0.002 | 0.002 | 0.005 | 0.008 |

* Denotes statistical significant at 95% level.

The results confirm that volatility of the overnight rate (panel 1) fell throughout the sample period. The conditional volatility estimate was higher before the 1996 introduction of the gilt repo market than immediately after ($h_t = 0.69$ before and $h_t = 0.40$ after 1996), even though the long-term component rose from 0.77 to 0.93. But since the 1996 reforms took place during a period of falling volatility, it is difficult to attribute this difference to the actual policy change. The conditional volatility and its components rose again after the Bank introduced daily repo transactions for its OMOs in 1997 ($h_t = 0.85$, $\rho = 0.98$). This result is surprising at first, as the March 1997 reforms increased the amount of collateral for use in the Bank's open market operations as well as the number of counterparties, and one might have expected a reduction in volatility. Closer inspection of Chart 2 shows, however, that overnight volatility indeed declined in the second and third quarter of 1997, before rising steeply in the last quarter of 1997 and the first quarter of 1998, thereby undoing any volatility-reducing effects the 1997 reforms may have

[32] *Bank of England Quarterly Bulletin*, August 1995, pages 225-27, and November 1995, pages 319-22.

had. Volatility estimates fell significantly after the 1998 and 1999 reforms ($h_t$ = 0.42 and 0.25 respectively), but persistence remained high ($\rho$=0.90 and 0.96, respectively).[(33)]

The table (panel 2) also shows that the two-week rate saw a marked fall in volatility and volatility persistence after the 1996 introduction of the gilt repo market. But, as in the case of the overnight rate, the lower two-week volatility of the second subperiod cannot solely be ascribed to the January 1996 reforms, as the downward trend had already started in the first subperiod (see Chart 3). The 1997 and 1998 reforms seem to have had no impact on two-week volatility, nor on its persistence. The 1999 reforms were followed by an increase in both volatility and persistence, even though they remained well below the values seen in the first subperiod.[(34)]

**Table J: Summary spread statistics (subperiods)**

| | **Libor overnight - repo** | | | **Two-week - repo** | | |
|---|---|---|---|---|---|---|
| (%) | Mean | St. dev. | Persistence | Mean | St. dev. | Persistence |
| 1994-96 | -0.67 | 0.87 | 0.16 | -0.25 | 0.26 | 0.86 |
| 1996-97 | -0.29* | 0.66 | 0.06 | 0.05* | 0.06 | 0.61 |
| 1997-98 | -0.25 | 0.99 | 0.11 | 0.11* | 0.07 | 0.77 |
| 1998-99 | -0.25 | 0.67 | 0.25 | 0.06* | 0.13 | 0.77 |
| 1999-2001 | -0.20 | 0.64 | 0.58 | -0.05* | 0.16 | 0.79 |

* Indicates that the mean spread is significantly different from the previous period spread.

Table J presents summary statistics for the repo spreads in different subperiods. The overnight and the two-week spread saw a significant reduction in both their mean and their standard deviation during our sample period. Both were significantly higher in the first subperiod, which preceded the January 1996 reform. Volatility of the overnight spreads was higher during the 1997-98 subperiod, reflecting the earlier mentioned rise in rate volatility. Finally, both spreads saw a decline in their persistence immediately after the 1996 reform. This proved, however, to be temporary, as can be seen from the persistence estimates for the later subperiods. In particular, the overnight spread was more persistent in the period after August 1999.[(35)]

(33) When running the C-GARCH regressions for the entire sample, but using dummies corresponding to the subperiods instead, we find that only the 1996 fall in overnight volatility was statistically significant.
(34) This is confirmed by the dummy regressions for the two-week rate. These regressions also indicate that two-week volatility after the 1999 reforms was significantly higher, and that this cannot be ascribed to the millennium changeover.
(35) This increase can partly be attributed to the millennium changeover. If we exclude December 1999 and January 2000 from our sample, the persistence of the overnight spread falls to 0.44, which is still above the previous period estimate of 0.25.

*6.3.2 The effect of higher volatility (subperiods)*

As we just showed, both overnight and two-week volatility and spreads varied throughout our sample period, so it is possible that by aggregating over time, the regressions of Section 6.2 failed to pick up any time-varying effects. We therefore re-estimated equation **(8)** for the subsamples. The $\pi$ coefficients are presented in Table K.

**Table K: Volatility transmission of overnight Libor and two-week rates (subsamples)**

| **Panel 1: Overnight volatility** | | | | | |
|---|---|---|---|---|---|
| **Impact on volatility of:** | 1994-96 | 1996-97 | 1997-98 | 1998-99 | 1999-2001 |
| Overnight rate | - | - | - | - | - |
| 1 week | 0.03 | -0.007 | -0.001 | 0.15 | -0.07 |
| 2 weeks | 0.88* | 0.005 | -0.007 | -0.007 | 0.10 |
| 1 month | 0.06 | -0.03 | -0.005 | -0.01 | 0.04 |
| 3 months | -0.01 | 0.004 | -0.0004 | -0.01 | -0.01 |
| 6 months | -0.008 | 0.001 | -0.01 | 0.0003 | 0.0006 |
| 12 months | -0.002 | 0.003 | -0.02 | 0.02 | -0.07 |
| **Panel 2: Two-week volatility** | | | | | |
| **Impact on volatility of:** | 1994-96 | 1996-97 | 1997-98 | 1998-99 | 1999-2001 |
| Overnight rate | 3.21 | -0.04 | -0.67 | -9.0 | -2.75 |
| 1 week | 0.18 | -0.07 | 0.43 | 0.14 | -0.14 |
| 2 weeks | - | - | - | - | - |
| 1 month | 0.02 | 0.04 | -0.003 | 0.006 | -0.03 |
| 3 months | -0.0005 | 0.006 | -0.01 | 0.002 | -0.003 |
| 6 months | -0.0001 | 0.001 | $-3.4\ 10^{-5}$ | -0.005 | 0.004 |
| 12 months | 0.002 | 0.01 | -0.05 | 0.001 | -0.01 |

* Indicates statistical significance at 95% level.

Generally, the impact of either overnight or two-week volatility on maturities one month and beyond is indistinguishable from zero, thereby confirming the results for the entire sample. Overnight volatility has a positive and statistically significant effect on two-week rate volatility prior to the 1996 introduction of the gilt repo market.(36) Thereafter, overnight volatility ceases to play any role at all. The impact of two-week volatility on both overnight and one-week volatility varies from period to period. It is the lowest immediately after the introduction of the gilt repo market in 1996, increases slightly after the 1997 reforms, but again none of the results have any statistical significance. Overall, the results of Tables G and K do not suggest that the relatively high overnight volatility that characterises the UK money markets affects the volatility of the longer-dated money market rates.(37)

(36) It is interesting to compare this result with Ayuso *et al* (1997) who for the period 1988-93 find significant transmission effects of overnight volatility at the three-month maturity, but not at one month or one year. They do not consider shorter maturities.

(37) For the period January 1999 to June 2001, the (unconditional) volatility of overnight Libor rates was equal to 0.60%, whereas volatility of the repo spread was 0.62%. The corresponding numbers for the euro area (EONIA) were 0.15% and 0.19%, and 0.25% and 0.19% for the United States (Fed funds rate).

### *6.3.3 The effect of wider spreads (subperiods)*

**Table L: The effect of deviations from the repo rate on money market volatility (subperiods)**

| **Panel 1: Libor overnight spread** | | | | | |
|---|---|---|---|---|---|
| **Impact on volatility of:** | 1994-96 | 1996-97 | 1997-98 | 1998-99 | 1999-2001 |
| Overnight rate | - | - | - | - | - |
| 1 week | 0.002 | 0.001* | $8.2\ 10^{-5}$ | 0.001 | 0.002 |
| 2 week | 0.0004 | $-4.5\ 10^{-5}$ | $-4.5\ 10^{-5}$* | -0.0001 | 0.002* |
| 1 month | 0.0001 | $-1.3\ 10^{-5}$ | $-1.5\ 10^{-5}$ | $-2.5\ 10^{-5}$ | 0.0003* |
| 3 months | $-1.3\ 10^{-5}$ | $3.2\ 10^{-5}$ | $-3.7\ 10^{-5}$* | $-7.1\ 10^{-5}$ | -0.0001 |
| 6 months | $-3.8\ 10^{-5}$ | -0.0001 | $-2.6\ 10^{-5}$ | -0.0002 | -0.0001 |
| 12 months | $-3.6\ 10^{-5}$ | $5.2\ 10^{-5}$ | $-3.1\ 10^{-5}$ | $-7.9\ 10^{-6}$ | -0.0001 |
| **Panel 2: Two-week spread** | | | | | |
| **Impact on volatility of:** | 1994-96 | 1996-97 | 1997-98 | 1998-99 | 1999-2001 |
| Overnight rate | 0.20 | -0.40 | 5.27 | -1.10 | 0.39* |
| 1 week | 0.015* | 0.05 | 0.002 | 0.10 | 0.035* |
| 2 week | - | - | - | - | - |
| 1 month | 0.002 | 0.001 | -0.0006 | 0.002 | 0.010* |
| 3 months | -0.0004 | 0.005 | 0.003 | -0.002 | -0.001 |
| 6 months | -0.0002 | 0.002 | $6.3\ 10^{-5}$ | 0.0002 | 0.0001 |
| 12 months | -0.0002 | 0.010 | 0.001 | -0.003 | -0.0002 |

* Indicates statistical significance at 95% level.

While the Libor overnight spread declined substantially over the sample period (Table J), the results in panel A1 of Table L indicate that its impact on the volatility structure of money market rates did not vary widely over time. The table further shows that the overnight spread significantly contributed to higher money market volatility in selected instances only. The overnight spread had some impact on one-week volatility in the 1996-97 subsample, and on two-week and three-month volatility in the 1997-98 period. The latter result coincides with narrower, but more volatile spreads (see Table J), whereas the former is somewhat more difficult to explain as the overnight spread was narrower and less volatile after the 1996 reforms. Finally, the overnight spread affected two-week and one-month volatility after 1999, but not the remainder maturities.

Panel 2 shows that in most subperiods, the two-week spread had no influence on money market volatility either. The two-week spread had some impact on the one-week spread in the first subperiod, but ceased to matter after the 1996 reforms. Interestingly, the two-week spread significantly affected volatility up to one month following the August 1999 reforms. This result is puzzling, since the two-week spread did not markedly widen in this period, though its volatility increased slightly (Table J).

### *6.4 Robustness checks*

Since 1997, an alternative overnight rate is available in the form of SONIA. SONIA (sterling overnight interest rate average) is a transaction-weighted average of overnight lending rates traded during the business day by seven London money market brokers. In Table M we re-estimate the C-GARCH model for SONIA rates, starting in February 1997, the earliest date for which data are available. For comparison purposes, we also re-estimate the model for overnight Libor, which, as mentioned earlier, is an end-of-day rate.

**Table M: C-GARCH estimation results for SONIA and Libor overnight (1997–2001)**

| **Panel 1: SONIA** | | | | | |
|---|---|---|---|---|---|
| Mean equation | | Variance equation | | Diagnostics | |
| $\gamma_0$ | 0.77<br>(3.62) | $\rho$ | 0.92<br>(27.81) | N<br>$R^2$ | 1148<br>0.27 |
| $\beta_1$ | -0.15<br>(-4.33) | $\omega_1$ | 0.06<br>(1.48) | ARCH-<br>LM | 0.10<br>0.11 |
| $\beta_2$ | -0.08<br>(-2.29) | $\phi_1$ | 0.03<br>(0.29) | $h_t$ | |
| $\beta_3$ | -0.11<br>(-3.63) | $\tau$ | 0.17<br>(27.79) | | |
| $\beta_4$ | -0.07<br>(-2.59) | | | | |
| $\delta$ | -0.35<br>(-12.78) | | | | |
| **Panel 2: Libor overnight** | | | | | |
| Mean equation | | Variance equation | | Diagnostics | |
| $\gamma_0$ | 0.82<br>(1.64) | $\rho$ | 0.98<br>(296) | N<br>$R^2$ | 1148<br>0.42 |
| $\beta_1$ | -0.22<br>(-6.13) | $\omega_1$ | -0.02<br>(-1.25) | ARCH-<br>LM | 0.004<br>0.29 |
| $\beta_2$ | -0.10<br>(-3.47) | $\phi_1$ | 0.73<br>(7.03) | $h_t$ | |
| $\delta$ | -0.54<br>(-14.25) | $\tau$ | 0.07<br>(11.44) | | |

First, we observe that the mean-variance specification is appropriate for SONIA as well. In the mean equation, we find the reaction to changes in the official rate to be slightly lower than for the LIBOR overnight rate ($\gamma_0$ = 0.77 versus 0.82), whereas the coefficient on the cointegrating vector is slightly lower as well ($\delta$ = -0.35 versus –0.54), though highly significant. In the variance equation, we find evidence of high persistence in the permanent component of both equations ($\rho$ = 0.92 and 0.98), but not in the transitory equation for SONIA ($\omega_1 + \phi_1$=0.09 versus 0.71).

More interesting is the conditional variance estimate $h_t$, which, with an average of 0.11 lies well below the estimated variance for the Libor overnight series ($h_t$ = 0.29). When re-estimating the C-GARCH model with dummies corresponding to the 1998 and 1999 reforms, we find that overnight Libor volatility was reduced after both reforms, whereas SONIA volatility rose. In both cases, the 1998 dummies were significant, and the 1999 dummies insignificant.(38) These results indicate that the two volatility series display somewhat different dynamics, which may point to intra-day patterns that may not be apparent in the Libor series. This is an issue that warrants further research.(39)

Finally, we re-estimated the transmission equations **(8)** and **(9)** using SONIA. We find that SONIA volatility does not affect any of the longer maturities. Sonia spreads over the repo rate have a small negative, but significant effect on two-week volatility only.(40)

### *6.5 VECM results*

In Sections 4 and 5.2, we explained how money market rates could be estimated as a VECM with the money market spreads over the repo rate serving as error-correction terms. In this section, we discuss the money market rate dynamics apparent from the VECM results. Table N shows the $\delta$ coefficients for the error correction terms, together with their t-statistics. The $\beta$ coefficient estimates are reported in Table O below.

**Table N: VECM results (1994-2001): Coefficients of error-correction terms**

| | Overnight | 1-week | 2-week | 1-month | 3-month | 6-month | 12-month |
|---|---|---|---|---|---|---|---|
| Overnight | -0.88 * | 0.59* | 1.51* | -2.04* | 0.11 | 0.44 | -0.31* |
| | (-26.31) | (4.15) | (5.89) | (-6.47) | (0.33) | (1.21) | (-2.06) |
| 1 week | -0.02* | -0.45* | 0.82* | -0.45* | 0.003 | 0.08 | -0.04 |
| | (-3.17) | (-18.29) | (18.47) | (-8.26) | (0.05) | (1.27) | (-1.64) |
| 2 week | 0.0001 | -0.02 | -0.18* | 0.15* | -0.01 | 0.07 | -0.04* |
| | (0.04) | (-0.87) | (-5.46) | (3.87) | (-0.29) | (1.47) | (-2.27) |
| 1 month | 0.0007 | -0.04* | 0.19* | -0.26* | 0.08* | 0.03 | -0.02* |
| | (0.34) | (-4.77) | (11.28) | (-12.62) | (3.81) | (1.34) | (-2.28) |
| 3 month | 0.003 | -0.015 | 0.04* | 0.03 | -0.17* | 0.14* | -0.02* |
| | (1.51) | (-0.17) | (2.63) | (1.60) | (-8.50) | (6.05) | (-2.13) |
| 6 month | 0.0002 | -0.003 | 0.02 | 0.005 | 0.07* | -0.16* | 0.08* |
| | (0.08) | (-0.36) | (1.24) | (0.24) | (3.33) | (-6.63) | (8.03) |
| 12 month | -0.0024 | -0.005 | 0.04 | -0.02 | -0.06* | 0.57* | -0.01 |
| | (-0.91) | (-0.44) | (1.80) | (-0.94) | (-2.35) | (2.01) | (-0.85) |

Coefficients $\delta$ on error-correction term, with columns 1 to 7 stating impact of the $i$-th error-correction term on rates in rows 1 to 7. t-statistics in parenthesis. Overnight rate is Libor. The VECMs use one lead for the two-week rate because of the earlier timing. * indicates significance at the 95% level.

Several results stand out. First, a large number of error-correction terms have significant coefficients, thereby validating our modelling approach. However, we do not find evidence of Hall *et al*'s (1992) observation that relatively more cointegration terms are required to explain short-term yields, than for longer-term yields. The highest and lowest number of significant

(38) The 1999 dummy was significant, however, when inserted in the permanent component for Libor volatility.
(39) Hartmann *et al* (2001) report that volatility of overnight rates in the euro area varies during the day, displaying a (weak) U-shape.
(40) The results, not reported here, are available from the author.

terms is found in the equations for one and twelve-month rates, respectively. In the remainder equations, three or four spreads enter significantly.

Second, except for the twelve-month rate, money market rates are significantly affected by their own repo spread. The highest $\delta$ coefficients (in absolute terms) are those for the overnight rate (-0.88) and the one-week rate (-0.45), indicating that stronger responses to changes in the official repo rate occur at the very short end of the yield curve.

Third, spreads between the two-week rate and the official repo rate significantly affect the dynamics of all other money market rates up to and including three months. The impact of the two-week spread on rate dynamics is relatively more important than on money market volatility, as we saw in Section 6.2.2 where the two-week spread influenced money market rate volatility up to one month (Table H).

Fourth, deviations of the overnight rate from the repo rate only affect the dynamics of the one-week rate (in addition to the overnight rate itself as mentioned above), but not those at the other maturities.(41) Here, the impact is weaker than the effect on volatility (Table H).

The remaining cointegrating equations have a more limited role in explaining rate dynamics. Generally, they enter significantly at their own and neighbouring maturities only. For example, the six-month spread contributes to rate changes at the three-month, six-month and twelve-month maturities.

**Table O: VECM results continued (1994-2001)**

| | Overnight | 1-week | 2-week | 1-month | 3-month | 6-month | 12-month | Repo |
|---|---|---|---|---|---|---|---|---|
| Overnight | -0.08* | -0.23 | -0.12 | 0.44 | 0.02 | 0.36 | -0.31 | -0.30 |
| 1 week | 0.005 | -0.08* | 0.24* | 0.12 | 0.01 | -0.06 | -0.05 | -0.01 |
| 2 week | -0.004 | -0.007 | -0.032 | -0.08 | 0.01 | -0.10 | 0.05 | 0.03 |
| 1 month | -0.0002 | 0.008 | 0.14* | -0.18* | 0.06* | 0.03 | 0.03 | 0.04 |
| 3 month | -0.002 | -0.01 | 0.10* | 0.09* | -0.02* | 0.01 | 0.08* | 0.01 |
| 6 month | -0.0003 | -0.02 | 0.01* | 0.06* | 0.04 | -0.24* | 0.09* | 0.04 |
| 12 month | 0.0005 | -0.007 | 0.06* | 0.06* | 0.07* | 0.15* | -0.25* | 0.02 |

Estimates of $\beta$ coefficients, with columns 1 to 8 stating the impact of rates $\Delta r_i$ on rates $\Delta r_j$ in rows 1-7. * indicates significance at the 95% level.

Short-term dynamics, captured by the $\beta$ coefficients, are shown in Table O. The most significant result is clearly the importance of the two-week rate. Changes in this rate lead to significant changes in the rates of all maturities, except the overnight rate. In contrast, the overnight rate has no significant effect on short-term dynamics of the yield curve.

Taken together, the VECM results suggest the following transmission mechanism. Changes in the policy rate first affect the two-week spread. They are then transmitted up the money market curve, via the two-week spread and in second instance via some of the higher-maturity

(41) We re-estimated the VECM using SONIA instead of the Libor overnight rate for the period 1997-2001, and compared this with a VECM using overnight Libor estimated over the same period. The results are qualitatively very similar and are therefore not reported.

cointegrating equations. In this adjustment process, the twelve-month spread stands out, in that it enters significantly in most equations. Hall *et al* (1992) observe a similar result and suggests that the spreads at the longer end of the money market curve contain information about future short-term rates.

We next re-estimated the VECMS with additional dummies representing the subperiods considered in Section 6.3.1.[42] Doing so does not alter any of the results discussed above. In addition, we find all dummies, except the 1997 one to significantly affect overnight and one-week rates. The two-week rate is affected by only the 1996 dummy. The 1997 dummy had no impact on the short end of the yield curve.

We conclude our analysis by discussing the impulse-response functions for the VECM of Tables N and O. The results are summarised in Table P, and Charts 4 and 5. Charts 4 and 5 show the reactions of money market rates to innovations in overnight and two-week rates, respectively. In the former case, most of the adjustment is seen in the one-week rate, and this seems to occur over two days. The one-month rate shows a small reaction, whereas the remainder rates barely move. In the latter case, the overnight and the one-week react to the initial shock, and the one-month rate to a lesser extent. Again, not much movement is seen in the higher maturities.

But as the results in Table P indicate, the impact of shocks on the variables in the system is generally weak and short-lasting.[43] Most of the coefficients in Table P are extremely low, and neither the two-week nor the overnight rates stand out in this respect. The only exception is the contemporaneous reaction of the overnight rate to its own innovations (0.69). One way of interpreting these results is that the money market transmission mechanisms described in the previous paragraphs are fairly efficient at absorbing shocks.

[42] The results are available from the author.
[43] It is a well-known problem that the results of this exercise are dependent on the ordering of the variables in the system. When considering alternative orderings, however, we find very similar results.

**Table P: Impulse response functions (1994-2001)**

| | s | Overnight | 1-week | 2-week | 1-month | 3-month | 6-month | 12-month |
|---|---|---|---|---|---|---|---|---|
| Overnight | 1 | 0.69 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5 | 0.01 | 0.04 | 0.07 | -0.04 | -0.01 | -0.01 | -0.01 |
| | 10 | 0 | 0.01 | 0.04 | -0.01 | -0.01 | 0 | -0.01 |
| 1 week | 1 | 0.05 | 0.11 | 0 | 0 | 0 | 0 | 0 |
| | 5 | 0.01 | 0.03 | 0.06 | -0.01 | 0 | 0 | -0.01 |
| | 10 | 0.01 | 0.01 | 0.04 | 0.01 | 0 | 0 | -0.01 |
| 2 week | 1 | 0.01 | 0.03 | 0.08 | 0 | 0 | 0 | 0 |
| | 5 | 0.01 | 0.01 | 0.05 | 0.01 | 0 | 0 | 0 |
| | 10 | 0 | 0.01 | 0.03 | 0.02 | 0.01 | 0 | 0 |
| 1 month | 1 | 0.06 | 0.01 | 0.01 | 0.04 | 0 | 0 | 0 |
| | 5 | 0 | 0.01 | 0.03 | 0.02 | 0.01 | 0 | 0 |
| | 10 | 0 | 0 | 0.03 | 0.02 | 0.01 | 0.01 | 0 |
| 3 month | 1 | 0 | 0 | 0.01 | 0.01 | 0.04 | 0 | 0 |
| | 5 | 0 | 0 | 0.02 | 0.02 | 0.03 | 0.01 | 0 |
| | 10 | 0 | 0 | 0.02 | 0.02 | 0.02 | 0.01 | 0 |
| 6 month | 1 | 0 | 0 | 0.01 | 0.01 | 0.02 | 0.04 | 0 |
| | 5 | 0 | 0 | 0.01 | 0.01 | 0.02 | 0.02 | 0.01 |
| | 10 | 0 | 0 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 |
| 12 month | 1 | 0 | 0 | 0 | 0.01 | 0.02 | 0.02 | 0.05 |
| | 5 | 0 | 0 | 0.01 | 0.01 | 0.02 | 0.02 | 0.04 |
| | 10 | 0 | 0 | 0.01 | 0.01 | 0.01 | 0.02 | 0.04 |

Reaction of rates in rows 1-7 to a one standard deviation innovation in the rates of columns 1-8, after *s* periods (*s*=1, 5, 10).

## 7. Conclusion

This paper presents a number of empirical tests that might be useful tools when evaluating the effectiveness of a central bank's open market operations over time. Our working hypothesis is that the central bank wishes to minimise deviations between key market rates and its policy rate. When applied to the United Kingdom's open market operations of the past seven years, we find that the central bank can best achieve this objective by focusing on the maturity chosen for its daily market operations. Specifically, our tests indicate that tighter spreads between the two-week market rate and the Bank of England's repo rate result in lower money market volatility at the short end of the money market curve. In contrast, our tests show that volatility of the two-week money market rate has little impact on longer-dated money market volatility. This suggests that direct efforts to reduce two-week volatility are less effective if not accompanied by an operational policy that aims for narrow spreads.

In contrast to many other central banks, the Bank of England does not employ an operating target for the overnight rate. While this results in relatively higher overnight volatility, our tests indicate that this volatility has no significant impact on longer-dated money market volatility. Likewise, we find that wider overnight spreads have little impact on the dynamics of money market rates. Hence, we find no evidence that allowing greater variation in overnight rates undermines efforts of the central bank to keep money market rates in alignment with its chosen monetary policy stance.

Our results further indicate that volatility at the very short end of the UK money market yield curve has declined significantly since the early 1990s. Volatility persistence has fallen as well, indicating that periods of unusually high volatility are more likely to be short-lived. The introduction of the gilt repo market in January 1996 was associated with lower money market volatility, although we have evidence that volatility had started to fall as early as mid-1995. Likewise, it is difficult to discern the effects of the 1997 reforms of the Bank of England's open market operations in the data. In contrast, the creation of a ceiling for overnight rates in June 1998 was more clearly associated with a reduction in volatility of end-of-day overnight rates.

The research also shows that it is very difficult to identify precisely the impact of specific policy reforms in the data. The interest rates studied here are set in markets that have been influenced by many factors besides changes to central bank operations. These include not only the introduction of the repo market, mentioned above, but also changes in payment and settlement systems and in the regulatory framework for the management of banks' liquidity.[44] Moreover, changes to central bank operations have not been wholly exogenous, but have responded in part to developments in markets.

(44) See Chaplin, Emblow and Michael (2000).

## Appendix

**Table Q: C-GARCH estimation results for the Libor overnight rate (subperiods)**

| | 1994-96 | 1996-97 | 1997-98 | 1998-99 | 1999-2001 |
|---|---|---|---|---|---|
| $\gamma_0$ | 1.73 | -0.59 | 2.44 | 0.99 | 0.12 |
| | (1.04) | (-0.03) | (1.03) | (0.94) | (0.14) |
| $\delta$ | -0.65 | -0.80 | -0.67 | -0.59 | -0.36 |
| | (-7.88) | (-7.57) | (-6.84) | (-5.96) | (-7.81) |
| $\rho$ | 0.77 | 0.93 | 0.98 | 0.90 | 0.96 |
| | (3.72) | (14.34) | (245) | (19.86) | (44.16) |
| $\omega_1$ | -0.13 | 0.04 | 0.03 | 0.04 | 0.11 |
| | (-0.80) | (0.71) | (1.28) | (0.41) | (1.27) |
| $\phi_1$ | 0.04 | 0.08 | -0.82 | 0.25 | 0.03 |
| | (0.04) | (0.21) | (-10.07) | (0.56) | (0.21) |
| $\tau$ | 0.17 | 0.01 | 0.01 | 0.13 | 0.04 |
| | (1.18) | (1.40) | (20.10) | (1.90) | (2.31) |
| N | 479 | 281 | 325 | 327 | 475 |
| $R^2$ | 0.47 | 0.48 | 0.46 | 0.40 | 0.28 |
| ARCH-LM | 0.02 | 0.37 | 0.10 | 0.02 | 0.015 |
| $h_t$ | 0.69 | 0.40 | 0.85 | 0.42 | 0.25 |

The $\beta$ coefficients are not reported.
In this and Table R, the subperiods are: April 1994-January 1996; February 1996-February 1997; March 1997-May 1998; June 1998-August 1999; September 1999-June 2001. Subperiods start on the day of the reform.

**Table R: C-GARCH estimation results for the two-week rate (subperiods)**

| | 1994-96 | 1996-97 | 1997-98 | 1998-99 | 1999-2001 |
|---|---|---|---|---|---|
| $\gamma_1$ | 0.84 | 0.39 | 0.17 | 0.23 | 0.36 |
| | (8.78) | (5.29) | (2.92) | (2.85) | (3.09) |
| $\delta$ | -0.08 | -0.25 | -0.11 | -0.13 | -0.13 |
| | (-4.06) | (-4.57) | (-2.99) | (-4.02) | (-6.28) |
| $\rho$ | 0.58 | 0.26 | 0.24 | 0.24 | 0.49 |
| | (11.28) | (0.24) | (0.31) | (0.34) | (2.84) |
| $\omega_1$ | 0.05 | 0.02 | 0.05 | 0.03 | -0.005 |
| | (0.84) | (0.05) | (0.81) | (1.22) | (-0.08) |
| $\phi_1$ | -0.001 | -0.03 | 0.02 | -0.02 | -0.18 |
| | (-0.01) | (-0.08) | (0.24) | (-0.12) | (-0.81) |
| $\tau$ | 0.14 | 0.08 | 0.05 | 0.04 | 0.07 |
| | (2.45) | (0.21) | (3.87) | (1.02) | (0.79) |
| N | 479 | 281 | 325 | 327 | 475 |
| $R^2$ | 0.17 | 0.24 | 0.13 | 0.09 | 0.10 |
| ARCH-LM | 0.04 | 0.14 | 0.43 | 0.29 | 0.34 |
| $h_t$ | 0.014 | 0.002 | 0.002 | 0.005 | 0.008 |

The $\beta$ coefficients are not reported. As before, the $\gamma_0$ coefficient is set equal to 0 in the two-week equation, and the estimate of $\gamma_1$ is reported. This takes into account the time difference between the two-week rate (recorded at 8:30 am) and the remaining rates (daily close).

## Charts 1A-G: Spreads over two-week repo rate (1994-2001)

(percentage points)

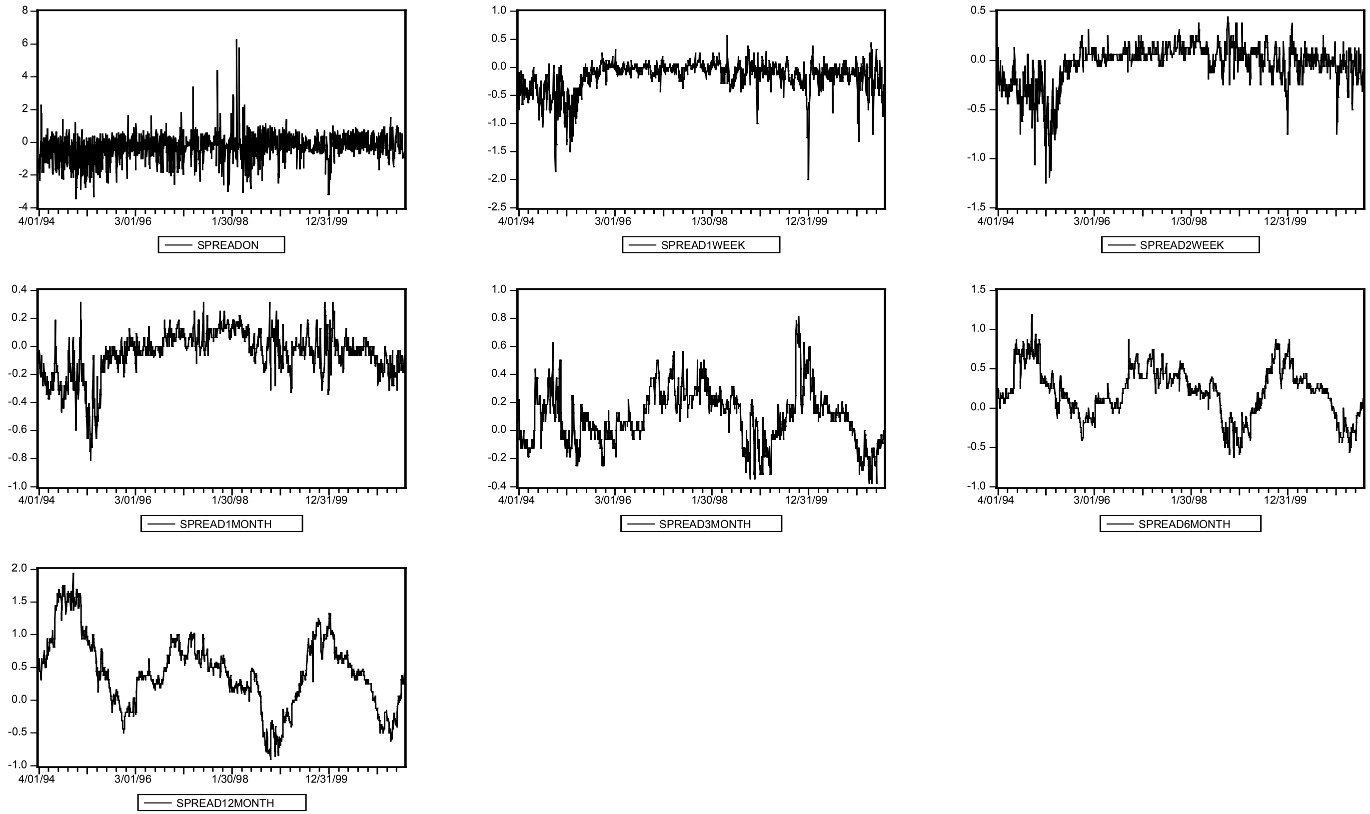


**Chart 2: Volatility of Libor overnight rate (1994-2001)**
**(per cent, estimated from C-GARCH model)**

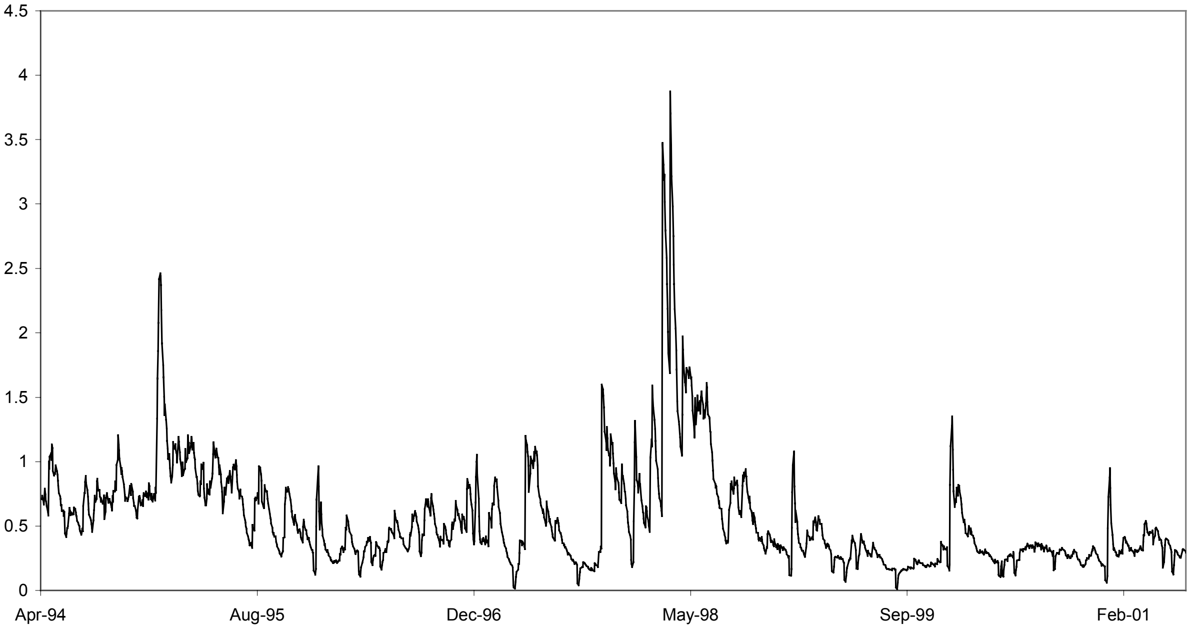
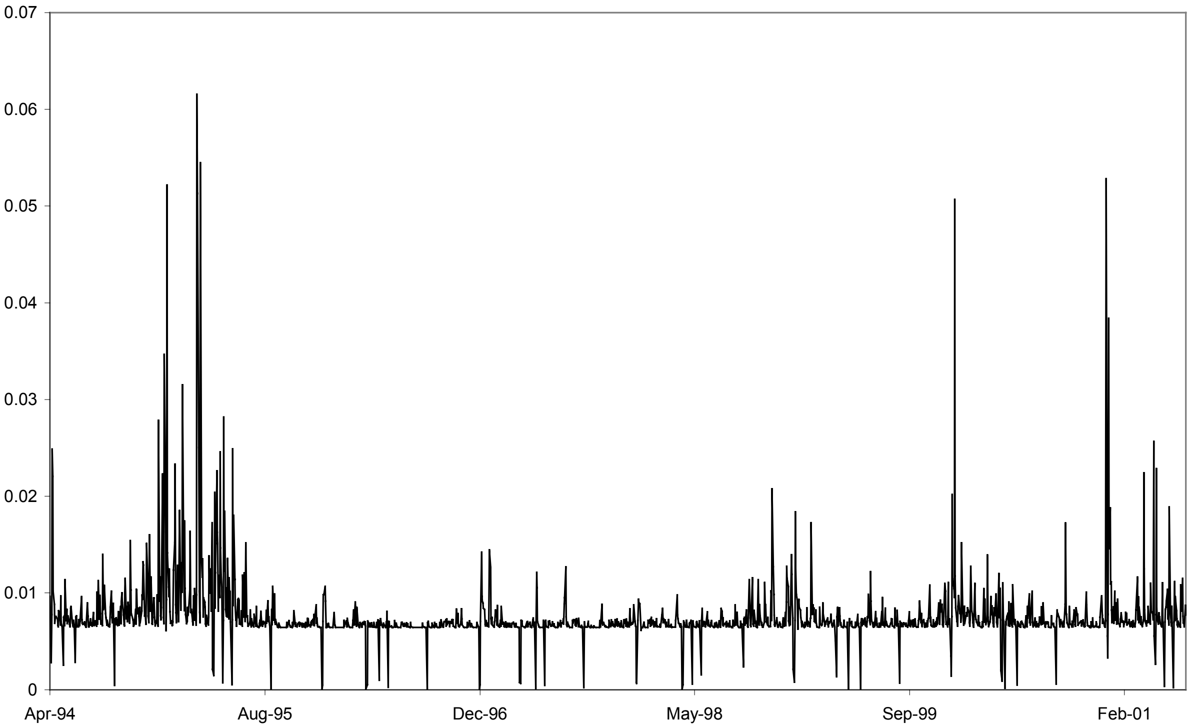
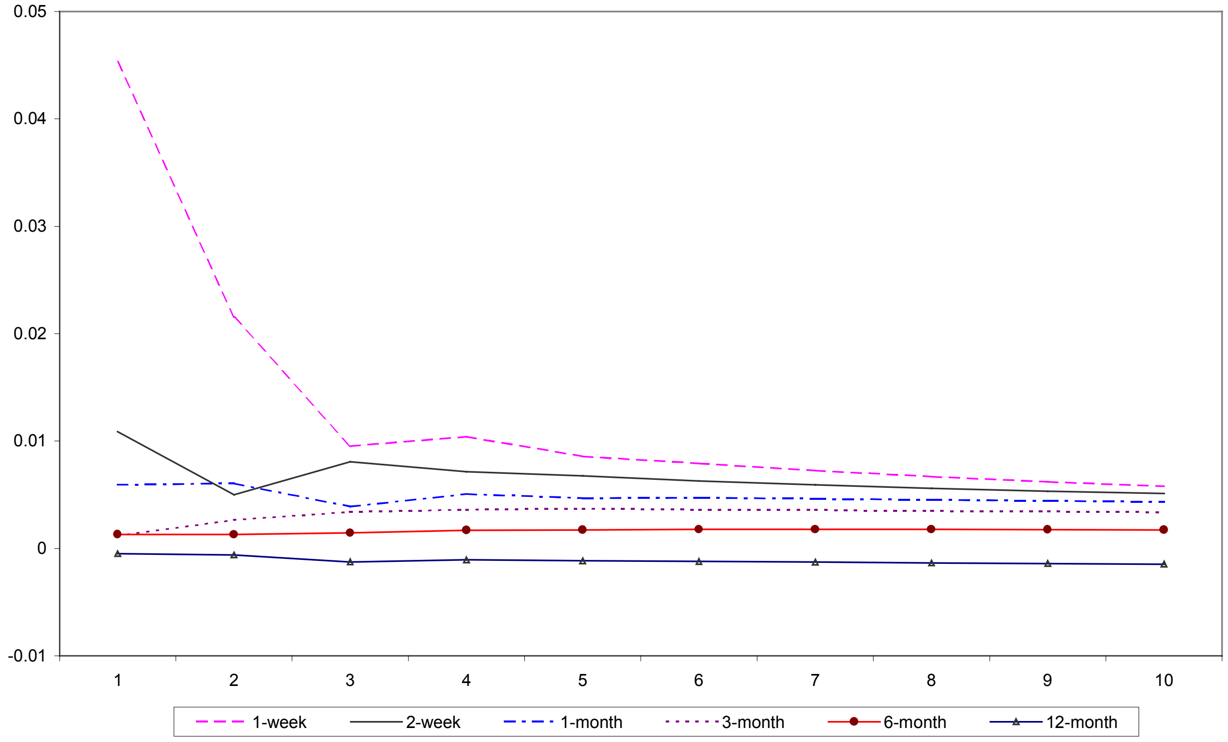


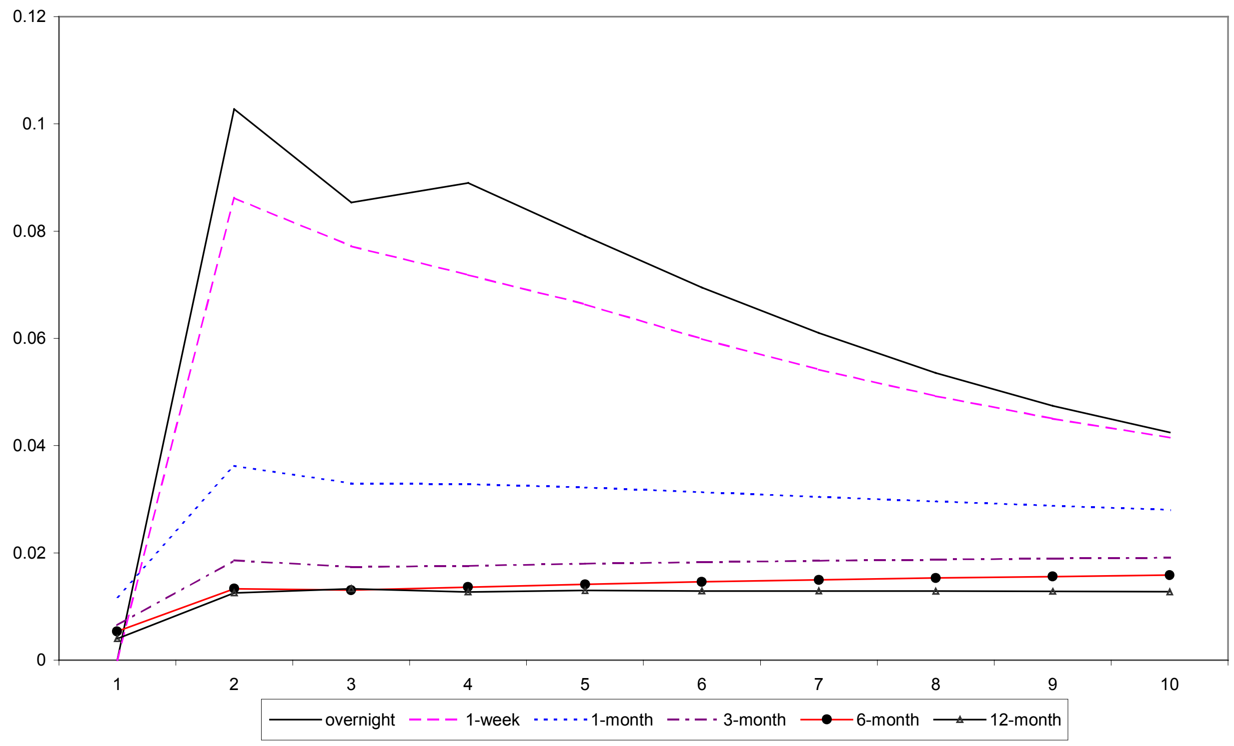

**Chart 3: Volatility of two-week rate (1994-2001)**
**(per cent, estimated from C-GARCH model)**



## Chart 4: Impulse response functions for shock in overnight rate




## Chart 5: Impulse response functions for shock in two-week rate



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