The Interrelationship Between Monetary Policy and the Interbank Money Market During the Financial Crisis

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List of Abbreviations

ADF	Augmented Dickey-Fuller
AF	Autonomous Liquidity Factors
B	Unexpected Bidders
CBR	Cover-to-Bid Ratio
CDS	Credit Default Swap
CET	Central European Time
ECB	European Central Bank
Eonia	Euro OverNight Index Average
EU	Euro Area
EUR	Euro
Euribor	Euro Interbank Offered Rate
EQR	Equity Ratio
FED	Federal Reserve System
GE	German Banks
HAC	Heteroscedasticity Autocorrelation-Consistent
OIS	Overnight Index Swap
IV	Implied Volatility
KfW	Kreditanstalt für Wiederaufbau
Libor	London Interbank Offered Rate
LIFFE	London International Financial Futures and Option Exchange
LR	Log Likelihood Ratio
LTRO	Long-term Refinancing Operation
MAD	Mean Absolute Deviation
MatMis	Maturity Mismatch

MBR	Minimum Bid Rate
MEAD	Median Absolute Deviation
MRO	Main Refinancing Operation
Obs	Observations
OLS	Ordinary Least Squares
OMO	Open Market Operation
OTC	Over-the-Counter
PB	Persistent Banks
Repo	Repurchase Agreement
RES	Remaining Required Reserves
Refcorp	Resolution Funfing Corporation
RMP	Reserve Maintenance Period
RTGS	Real Time Gross Settlement
SNB	Swiss National Bank
sLTRO	Supplementary Long-term Refinancing Operation
TA	Tradable Assets Over Balance Sheet Total
TSLF	Term Securities Lending Facility
US	United States
Vstoxx	Euro Stoxx 50 Volatility Index

3M	Three Month
6M	Six Month
12M	Twelve Month
1W	One Week

Chapter 1

Introduction

> *"It is a melancholy fact that each generation must relearn the fundamental principles of money in the bitter school of experience"*
> (Maurice Allais, 1987)

The monetary policy of major central banks is assigned the primary role in short-term aggregate demand management through the manipulation of a suitable short-run interest rate. The monetary transmission mechanism generally ensures that this policy affects longer-term interest rates, asset prices and expectations of future inflation. The financial crisis that began in August 2007, however, has raised serious question marks about the existing consensus on monetary policy. It is therefore natural to ask whether the events of the past four years highlight fundamental flaws in the policy frameworks of central banks. This thesis analyzes some of the core aspects of the monetary policy framework on the basis of recent events and discusses how central banks may modify their operational settings for the post-crisis practice, focusing in particular on the European Central Bank (ECB).

In general, the ECB implements its monetary policy through a framework in which the banking sector operates in a liquidity deficit vis-á-vis the Eurosystem. The weekly main refinancing operations (MROs) cover the bulk of banks' liquidity demand and play the pivotal role in signalling the monetary policy stance. Until October 2008, MROs were conducted as variable rate tenders, i.e. as price-discriminatory multi-unit auctions where banks are allowed to submit multiple price-quantity bids. Banks that intended to participate in these auctions were required to place their bids higher than a pre-announced minimum bid rate. The ECB follows usually a liquidity neutral policy, i.e. it allocates only a liquidity amount in its MROs that allows banks a smooth fulfillment of the reserve requirements that they are obliged to hold with the Eurosystem. Hence, banks that do not manage to cover their funding needs in the auction must borrow in the secondary money market. That is, instead of refinancing in the ECB's repo auctions, an individual bank may also obtain central bank money from the secondary money market. In fact, between two consecutive MROs, the ECB is usually not actively managing liquidity supply.[1] Therefore, banks generally need to resort to the secondary money market to satisfy their funding needs.

The funding conditions in money markets substantially affect the stability of the banking sector and the liquidity situation of broader financial markets, see e.g. Brunnermeier and Pedersen (2009) and Nyborg and Östberg (2010).[2] Thus, when financial institutions suffer from a serious liquidity bottleneck, central banks may want to prevent these tensions from spilling over to other segments of the financial system. For instance, central banks could respond with a substantial adjustment of their funding supply. Yet, the success in coping with liquidity demand shocks ultimately depends on the accurate assessment of the determinants of aggregate demand for central bank liquidity. Assessing the aggregate demand for reserves is particularly important and essential if the demand itself is determined by financial market liquidity and the stability of the banking sector. To shed more light on the interrelationship between liquidity of different markets, Chapter 2 identifies an aggregate liquidity demand function for the German banking sector and investigates how it responds to variables derived from economic theory.

[1] In contrast to the U.S. Federal Reserve System, the ECB makes only very infrequent use of its so called fine-tuning operations, which are usually conducted with a small pre-selected group of large banks at very short maturities.

[2] Note that throughout the whole thesis, we will use the term secondary money market, interbank money market and money market interchangeably.

For this analysis, we have access to the unique record of the demand schedules of all German banks that submitted to the ECB's MRO auctions from June 2000 onwards. The observed price-quantity pairs provide a good indication of banks' actual willingness to pay for central bank money. Following the methodology of Berg et al. (1998) and Boukai and Landsberger (1999), we identify an aggregated bid curve by applying a three-parameter logistic model to banks' cumulated bidding behavior. In a next step, we relate the determinants of liquidity demand raised in the literature to specific variables in order to assess the explanatory power of different theories. This analysis strongly benefits from our unique data set on the daily reserve holdings and the monthly balance sheet statistics of each German financial institution.

Our findings show that the more unevenly distributed liquidity holdings are in the German banking sector, the larger is the premium that banks are willing to pay for funding in the ECB's auctions. This might result from a fear that some banks obtain market power in the interbank money market and squeeze liquidity-short banks. Second, our results indicate that more volatile asset prices increase the aggregate demand for central bank reserves. In that sense, we complement Nyborg and Östberg (2010). While they show that tensions in the interbank money market can feed into asset prices of the broader financial system, our paper provides strong evidence that high volatility of asset prices can affect banks' demand for liquidity. The strong evidence for both channels suggests that liquidity spirals (Brunnermeier, 2009) exist. Third, we find that a large variation of banks' equity ratios, as a measure for the heterogeneity of credit risk in the banking sector, induces both a more aggressive bidding strategy and a bid shading behavior. Fourth, our analysis reveals that an increase in the ratio of banks that persistently refinance through the ECB's auctions during the financial crisis raises the price elasticity of reserve demand. Fifth, a large stock of tradable assets that banks hold on the balance sheets is shown to reduce banks' refinancing need through the primary money market. And sixth, our results suggest that a high level of maturity mismatch of the German banking sector increases banks' dependency on the primary money market. To conclude, our results show that tensions in financial markets and adverse shocks to the stability of the banking sector increase aggregate liquidity demand.

These findings challenge the liquidity neutral allotment policy, followed by the ECB until October 2008. With a neutral liquidity provision, a central bank does not accommodate shocks to the aggregate reserve demand. Therefore, an increase in aggregate reserve demand resulting from detrimental shocks to the financial system's stability leads to an increase in the equilibrium rate in the primary money market and supposedly also to higher rates in secondary money markets. This in turn may destabilize liquidity-short banks aggravating tensions in the financial system. For instance, if banks' liquidity demand increases in the primary market for reserves because asset markets happen to be more illiquid, the equilibrium rate will increase. The resulting tensions in the money markets impair the liquidity of financial markets further, raising the demand for central bank reserves. Consequently, a liquidity neutral allotment policy gives rise to self-enforcing liquidity crises. Changing the pattern of the liquidity provision albeit keeping the aggregate supply of reserves over the reserve maintenance period at the level of the required holdings is according to our findings just not sufficient to break this vicious circle. In this respect, our results strongly support the ECB's decision to abandon its liquidity neutral allotment policy in October 2008. For the post-crisis conduct of monetary policy, however, the outcome of this chapter advised against the resumption of the neutral liquidity provision policy. Therefore, future research should investigate the pattern of banks' liquidity holdings from a micro perspective conditional on the aggregate liquidity demand. Also, to improve our understanding of how liquidity spirals work in more detail, one could assess the bank-specific sensitivities to changes of different asset classes from a disaggregated perspective.

Chapter 3 takes a closer look at the first step of the monetary transmission process in the euro area, i.e. the relation between the ECB's main refinancing (MRO) rates and the short-term money market. The liquidity supply through MROs should ensure that short-term money market rates closely follow the MRO rates and that their volatility remains well contained, see e.g. Cassola and Morana (2008) and Ejerskov et al. (2008). This central aim of monetary policy implementation has never been an easy task. Even before the financial crisis, a puzzling and unintended upward trend in the spread between the European overnight rate (Eonia) and the MRO rates indicated that the monetary transmission mechanism is not sufficiently understood, see Linzert and Schmidt (2011). Since the start of the financial crisis, spreads between the ECB's main refinancing rates and the short-term money market rates have been huge and persistent. Hence, we investigate how the European money market responds to MRO auction outcomes before and after August 2007.

Our results show that the recent crisis significantly impeded the first step of the monetary transmission mechanism. Before the financial crisis, we confirm a stabilizing level relationship between the overnight rate Eonia and MRO rates. If e. g. the spread between the Eonia and the new MRO rate was above average, the Eonia would adjust accordingly. Since the outbreak of the crisis, however, the relationship between MROs and the money market have been distorted in two important ways. First, we find that the level of money market rates has been disconnected from MRO rates since the outbreak of the crisis in August 2007. In contrast to the pre-crisis period, MRO auction outcomes fail to stabilize money market rates during our sample of the financial crisis. This implies that the first step of the transmission channel of monetary policy has been interrupted. The second change in the relationship between MRO auctions and the money market concerns the role of the MRO spread, i. e. the difference between the quantity-weighted average and the marginal MRO rate. While MRO spreads have been typically small before the crisis, in the crisis MRO spreads were inflated by safety bids reflecting the increased uncertainty of banks about their refinancing conditions. In contrast to the stabilizing impact of MRO auctions before the crisis, the response of money market rates to the MRO spreads destabilized money market conditions by exacerbating the disconnection of money market rates from the policy-intended interest rate level. This self-enforcing destabilization is also found for the level of longer-term money market rates. Both findings strongly support the ECB's decision made in October 2008 to re-stabilize banks' refinancing conditions by adopting a fixed rate full allotment policy in its MROs and also in its longer-term refinancing operations (LTROs).

For the post-crisis period, we conclude that the Dutch or competitive auction format as recently conducted by the U.S. Federal Reserve System in its term securities lending facility (TSLF) could be an alternative to the ECB's standard variable rate tender, see e.g. Fleming et al. (2010). In the competitive auction format, the probably destabilizing MRO spreads are always zero because each successful bidder pays simply the uniform rate. A natural path for further research will be a study of the implications of such an auction format for the monetary transmission mechanism in the euro area.

Based on the findings presented in Chapter 3, the fourth chapter is devoted to the developments in the longer-term money market interest rates during the financial crisis until December 2009. The euro area financial system has a bank-centered structure and as such, the unsecured money market rates determine short-term bank loan and deposit rates and thereby financing conditions for households and businesses. Hence, the prevailing interest rates in the unsecured money market segment play a key role for the effectiveness of monetary policy and the functioning of the transmission mechanism in the euro area. After August 2007, however, money market interest rates rose to unprecedented levels reflecting banks' re-assessment of borrower's creditworthiness and their willingness and capacity to lend. This caused a tightening of credit standards for both businesses and households, see European Central Bank (2010). These developments have called into question whether monetary policy can effectively steer short-term money market rates in such an environment.

The aim of this chapter is therefore to investigate the effectiveness of monetary policy in steering money market rates during the crisis. For this purpose, we study two aspects: First, we explore whether markets' interest rate expectations are adequately reflected in the shape of the money market yield curve. Second, we analyze the extent to which the ECB's crisis related (non-standard) monetary policy measures have been effective in reducing money market rates. To that aim, we focus on the daily dynamics of the three-month, six-month and twelve-month euro interbank offered rates (Euribor) during the period March 2004 through December 2009.

Our results show that during the financial crisis the Euribor rates significantly deviate from the central path expected by market participants for monetary policy in the euro area. For the period from August 2007 through October 2008, we find that the dispersion of market expectations around this central scenario has increased and thereby significantly contributed to higher Euribor rates. While some part of the increased uncertainty can be described by elevated risk measures, most of the uncertainty can be attributed to the ECB's MRO auction outcome. Additionally, our results indicate that from August 2007 through October 2008 longer-term money market rates have been heavily impacted by risk concerns, predominantly by liquidity premia.

For the period after October 2008, higher Euribor rates seem to be due to both liquidity and credit risk measures. Our results suggest that uncertainty in market expectations plays no significant role. Yet, our results reveal significant persistence in Euribor rates. Compared to the period before mid 2007, we observe a fourfold, sixfold, and tenfold increase in the persistence of the three-month, six-month, and twelve-month Euribor rates, respectively. This finding suggests that potential shocks may last longer in Euribor rates and thereby severely impede their controllability via standard monetary transmission channels. All in all, the results point to the weakened ability of the central bank to steer money market rates.

At the same time, however, we provide strong evidence that the ECB's crisis-related (non-standard) monetary policy measures have proven to be effective in reducing money market rates. During our sample of the financial crisis the significant expansion of the central bank balance sheet and the conduct of fixed rate tenders with full allotment have exerted a significant influence on the dynamics of money market rates at three-month, six-month, and twelve-month maturities. In particular, our results indicate that the ECB's net increase in outstanding open market operations as of October 2008 accounts for at least a 60 basis point decline in Euribor rates. We conclude that part of the loss in the effectiveness of monetary policy during the financial crisis via the traditional interest rate channel was compensated by the effective use of liquidity operations affecting money market rates beyond the daily maturity. Therefore, our results clearly show that central banks indeed have adequate tools at their disposal to conduct effective monetary policy, even in times of crises. Future research may analyze the extent to which other non-standard measures, such as the Eurosystem's covered bond purchase programm, have helped to alleviate the strains in the money market.

The large risk premia and heightened money market rates were not only observed in the euro area. Almost all major central banks were concerned with increased interest rates, in particular in the longer-dated maturity segment. In Switzerland, however, these developments were only moderately severe. In fact, risk premia seemed to be at very low levels as for instance indicated by the respective Libor-OIS spreads. Throughout the financial crisis, this has drawn a great attention to the Swiss National Bank (SNB) not least because of its unique operational framework. While other central banks use more or less explicit targets for the overnight rate to signal the policy-intended interest rate level, the SNB announces a target range for the three-month term money market rate Libor. In Chapter 5, we will therefore study the working of the SNB's unique operational framework. The empirical analysis focuses on how the three-month term interest rate responds to various policy-relevant factors including e.g. deviations of the Libor from its target, changes in risk premia, market expectations, and the SNB's supply of reserves. In order to capture a possible change in interest rate dynamics and the SNB's monetary policy, the analysis is employed for the period before and after the outbreak of the financial crisis separately.

Our empirical results show that the SNB controls the three-month Libor through both, 'words' and 'deeds'. First of all, the announced target rate itself is found to have an influence on the Libor. Moreover, the prevailing Libor also depends on the expected path of the target range. This highlights the importance of expectations management by the SNB via e.g. interviews and speeches. The SNB's communication of current and future target rates is substantiated by a very active liquidity management. The most important policy instrument, in this respect, seems to be the daily repo auctions with one-week maturity. The repo volume allotted in these auctions determines the level of reserves and, in addition, the pre-announced repo rate governs the one-week repo rate in the interbank money market. Hence, we conclude that the repo rate can be seen as the SNB's intermediate policy rate to manage the three-month Libor.

Shifting the emphasis from the overnight rate to a longer-dated interest rate may indeed provide a central bank with sufficient leeway to deal with financial shocks without having to declare a change in the stance of monetary policy. Therefore, both the overnight rate and the three-month rate targeting might lead to similar outcomes in normal times, when large shocks are absent and spreads between interbank money market rates are low and stable. During financial crises, however, the behavior of Swiss interest rates suggests that the SNB's three-month rate targeting have some additional features that could make it interesting for other central banks to apply. In fact, the transparency of the SNB's interest rate policy during the recent crisis might have contributed to keep the risk premia revealed by the Libor-OIS spreads relatively low.

Chapter 6 of this thesis will summarize all major findings and provide a final discussion of their implications for the future conduct of monetary policy. In addition, I will highlight other question marks that the financial crisis has raised about the existing monetary policy paradigm that will be part of my future research agenda.

Chapter 2

The Determinants of Market Demand for Liquidity

“The fact that it is commonplace to find economists treating the monetary base and/or the money stock as exogenously determined in their models does not mitigate the error; the fact is that this approach is simply incorrect”
(Charles Goodhart, 1987)

2.1 Introduction

The availability of funding in money markets has a major impact on the stability of the banking sector and on the liquidity of broader financial markets, see e. g. Brunnermeier (2009) and Nyborg and Östberg (2010). In order to contain the pressure in money markets during the recent financial crisis and avoid a spill-over of those tensions to other segments of the financial system, central banks accommodated shocks to the demand for reserves and heavily adjusted their liquidity supply, see e. g. European Central Bank (2010). Yet, central banks’ success in coping with liquidity demand shocks crucially depends on the accurate assessment of the determinants of market's demand for central bank liquidity. Assessing the aggregate demand for reserves is particularly important and essential if the demand itself is determined by financial market liquidity and the stability of the banking sector. To shed more light on the interrelationship between liquidity of different markets, this paper identifies an aggregate liquidity demand function for the German banking sector and investigates how it responds to variables derived from economic theory.

In its weekly-held main refinancing operations (MROs), the European Central Bank (ECB) auctions liquidity for a period of one week. During our sample period from June 27, 2000 to October 15 2008, the MROs were conducted as pay-your-bid auctions, i.e. as multi-unit price-discriminatory auctions.[3] Hence, the price-quantity pairs that financial institutions place in these auctions provide a good indication of bank's actual willingness to pay for liquidity. We have access to the unique record of the demand schedules of all German banks that submitted to the ECB's money market auctions from June 2000 onwards. This allows us to derive an aggregate demand function for the complete German banking sector. Following the methodology of Berg et al. (1998) and Boukai and Landsberger (1999), we identify an aggregated bid curve by applying a three-parameter logistic model to banks' cumulated bidding behavior for each auction within our sample. In a second step, we explore the determinants of the three model parameters that describe the aggregated demand functions. This analysis strongly benefits from our unique data on the daily reserve holdings and the monthly balance sheet statistics of each German financial institution.

We find several factors that affect the level and slope of the aggregate demand for reserves. First, our results suggest that before the crisis a larger dispersion of banks' reserve fulfillment increased German banks' willingness to pay for central bank liquidity and lowered the price elasticity of liquidity demand. Also during the crisis, a larger dispersion of banks' reserve fulfillment induces more aggres-

[3]Prior to June 2000 and in the aftermath of the Lehman-collapse, the Eurosystem applied a fixed-rate tender rather than a variable rate tender. For further details, refer to European Central Bank (2011).

sive bidding behavior. In contrast to the pre-crisis period, however, this effect is observed in all *but* the last MRO of a reserve maintenance period. Second, we find that during the crisis higher volatility of stock prices significantly increased the demand for reserves and banks' willingness to pay. Similarly, only after August 2007 a large dispersion of banks' equity ratio elevates banks' willingness to pay for reserves and induces higher dispersion of bids. A large share of tradable securities on banks' balance sheets decreased the level of the liquidity demand before the crisis. During the crisis, a larger share of tradable assets leads to a lower willingness to pay. Finally, we find that a rise in the ratio of banks that persistently refinance through central bank operations increases both the level of reserve demand as well as its price elasticity. We also test whether liquidity demand is determined by the average maturity mismatch on German banks' balance sheets. Our results suggest that a high level of maturity mismatch increases banks' dependency on the primary money market both before and during the recent financial crisis.

Our findings confirm a number of recent theoretical predictions. The observation that a large dispersion of liquidity holdings in the banking sector leads to an upward shift of the reserve demand in the primary money market implies that frictions in the money markets prevail. The ECB follows a neutral liquidity policy, i.e. its allotment complies with the aggregate amount of reserves that allows banks' smooth fulfillment of reserve requirements, see European Central Bank (2004a). Against this background, a higher dispersion among banks' reserve fulfillments indicates that larger amounts of liquidity need to be reallocated within the banking sector. Thus, our findings show that the larger the need for liquidity reallocation through the secondary money market is, the more willing are banks to pay for funding in the euro area primary market for reserves. In that sense, our study confirms the argument pointed out by Freixas et al. (2010), namely that larger idiosyncratic liquidity shocks in the banking sector partially inhibit the liquidity insurance role of banks and thus lead to higher secondary money market rates. Their argument, though, rests on Bhattacharya and Gale (1987) and Bhattacharya and Fulghieri (1994) on the basis of the assumption that bank-specific liquidity shocks are unobservable and banks therefore tend to free-ride on the secondary market for central bank liquidity. This in turn is argued to result in an under-investment in liquidity and elevate money market rates. Our results could, in addition, also reflect the fear of money market squeezes, as pointed out by Nyborg and Strebulaev (2004). As a result of the ECB's neutral liquidity provision, some banks with excess reserves might gain market power over liquidity-short banks. Thus, the more asymmetric liquidity is distributed in the banking sector, the larger is the fear of such market squeezes and the more banks are willing to pay in the primary money market.[4] In this regard, our paper builds on the findings of Fecht et al. (2011) obtained for the period 2000 to 2001.

Our result regarding the heterogeneity in banks' equity ratios fits very well the predictions of recent theoretical work that highlights the role of asymmetric information about credit risk in the secondary money market. For instance, Freixas and Jorge (2008) point out that a higher dispersion of the credit risk increases the information risk premium in the secondary money market. Furthermore, it might induce higher incentives for liquidity hording and contribute to a market dry-up, as shown by Heider et al. (2010). This, in fact, might explain why we find a significant influence of the dispersion of the equity ratio only in the crisis period.

This paper also relates to the theoretical literature that suggests an interplay between liquidity needs and prices in the broader financial markets, see e. g. Allen and Gale (1994), Acharya et al. (2009), and Brunnermeier and Pedersen (2009). Under cash-in-the-market pricing, liquidity shocks affect asset prices and lead to a higher price volatility. At the same time a higher asset price uncertainty induces banks to hold larger liquidity buffers as pointed out by Allen and Gale (2004). Brunnermeier and Pedersen (2009) find that more volatile asset prices tighten financial institutions' liquidity constraints and thereby elevate the demand for central bank reserves. And vice versa, they also point out that tighter liquidity constraints may also trigger a feedback effect on asset price volatility. Both mutually reinforcing dynamics generate a liquidity spiral where tighter liquidity constraints increase volatility of asset prices which in turn exacerbate liquidity constraints even further. Nyborg and Östberg (2010) provide strong empirical evidence for the former effect, i.e. that tensions in the interbank money market give

[4] See also Acharya et al. (2008) for similar arguments.

rise to an increased volatility in asset prices in the broader financial markets. Our analysis refers to the latter channel and shows that a dry-up of asset market liquidity associated with a higher price volatility indeed increases banks' demand for liquidity. Nyborg and Östberg (2010) together with our paper imply that liquidity spirals exist.

Our paper also complements earlier empirical studies that explore banks' bidding behavior in central bank auctions from a bank's individual perspective, see e. g. Bindseil et al. (2007), Bindseil et al. (2009), and Cassola et al. (2009). These papers show that money market conditions significantly affect bank's *individual* demand behavior and thus the auction outcome. However, these papers do not intend to explain the determinants of aggregate market demand. To the best of our knowledge, Berg et al. (1998), Boukai and Landsberger (1999) and Preget and Waelbroeck (2005) are the only empirical studies on aggregate bid functions. But they argue that fluctuations from one auction to the other can be explained by random perturbations on the parameters of the aggregate demand curve.[5] Using Israeli, Norwegian and French data sets, respectively, these authors therefore solely focus on an identification of an econometric model that describes the aggregate behavior of Treasury bill auction participants, observed during the period 1995 - 1997. The current paper is the first study that we are aware of which (i) estimates an aggregate demand function for liquidity for the German banking sector, (ii) captures the period as of March 2004 through October 2008, and most importantly (iii) relates the empirical approach to economic theory to test theoretical predictions.

The remainder of the paper is organized as follows. The next section briefly describes the Eurosystem's operational framework. Section 2.3 identifies a market demand function for the German banking sector and discusses the results. In Section 2.4, we elaborate on the theoretical literature to derive testable predictions regarding the determinants of market demand for central bank liquidity. Further-

[5] Even though Preget and Waelbroeck (2005) attempt to attribute the variations of aggregated bid curves across auctions in France to some random economic variables, they also conclude that the bulk of fluctuations are mostly random.

more, we use our data set to test these hypotheses. Section 2.5 summarizes our key results and draws some policy conclusions.

2.2 Eurosystem's Institutional Framework

In the euro area, the demand for liquidity is predominantly driven by reserves that banks are obliged to hold with the Eurosystem. These reserve requirements are specified as an average of the end-of-day reserve balances over a reserve maintenance period (RMP). In our sample a maintenance period is defined as the cycle between the first Governing Council meeting of two consecutive months and might therefore have a duration ranging from 28 to 43 days. Reserve requirements amount to 2% of a bank's short-term liabilities held by private non-banks as reported in the balance sheet of the respective bank, two months prior to the beginning of the maintenance period.[6] While there is an interest rate paid on required reserve holdings, reserves held in excess remain unremunerated.[7]

However, the sum of the autonomous liquidity factors is larger on the liability side than on the asset side of the Eurosystem's balance sheet. This implies that the euro area banking sector operates in a liquidity deficit vis-a-vis the Eurosystem. That is, banks need to get refinancing from the European Central Bank (ECB) in order to comply with their reserve requirements. The ECB provides liquidity in a neutral fashion, i.e. its liquidity allotment is oriented towards the estimated liquidity needs of the euro area banking sector. Prior to each auction, the ECB publishes its

[6] This consists of overnight deposits, deposits with an agreed maturity of up to two years, deposits redeemable at notice up to two years, and issued debt securities with agreed maturity of up to two years held by households, the non-bank corporate sector, and banks from outside the euro area.

[7] The Eurosystem applies a certain discretion on how to penalize under-fulfillments. Nevertheless, the penalty rate imposed on reserve deficiencies is the highest interest rate charged such that under-fulfilling the reserve requirements becomes the costliest option.

benchmark allotment such that all banks are informed about the amount the ECB deems appropriate to allocate, see European Central Bank (2004b).[8]

During our sample, the ECB mainly allocates liquidity through an auction mechanism to the banking sector. In this respect, a pivotal role has been assigned to ECB's main refinancing operations (MROs). These operations are conducted on a weekly basis. In these auctions, banks bid for reversed repurchase agreements (repos) with a maturity of one week.[9] Unlike the U.S. Federal Reserve System (FED), any bank that holds reserves with the Eurosystem and meets several eligibility requirements may participate in these tender operations. In the first meeting of each month, the Governing Council of the Eurosystem sets a minimum bid rate that serves as the key monetary policy interest rate. Banks that intend to participate in an MRO are required to place their bids higher than this minimum bid rate. The MROs follow a multi-unit pay-your-bid auction format where banks are allowed to submit *multiple* price-quantity bids. That is, each bidder may submit up to 10 bid-quantity pairs where the tick size is 1 basis point and the quantity multiple is 100,000 euros. These bids provide a good indication of bank's willingness to pay for central bank liquidity and thus allow us to study the aggregate demand behavior. But it should be noted that this auction mechanism might induce strategic bidding behavior by means of bid shading, see e. g. Nautz and Wolfstetter (1997). That is, the reported bid-quantity schedules might not reflect the exact willingness to pay. Nevertheless, this is the best information available under a multi-unit discriminatory auction format.

The liquidity obtained through the ECB is redistributed in the secondary money market. That is, instead of refinancing in the ECB's repo auctions, an individual bank may also obtain central bank money from the secondary money market. In fact, between two consecutive MROs, the ECB is usually not actively managing liquidity supply. In contrast to the U.S. FED, the ECB makes only very infrequent

[8]The benchmark allotment is the amount normally required to establish balanced conditions in the short-term money market, given the ECB's complete liquidity forecast. Balanced liquidity conditions should normally result in an overnight rate close to the ECB's policy rate, see European Central Bank (2003)

[9]Beyond the MROs, the Eurosystem also facilitates liquidity through long-term refinancing operations (LTROs). But these operations are beyond the scope of this chapter.

use of its so called fine-tuning operations, which are usually conducted with a small preselected group of large banks at very short maturities. Thus, between two consecutive MROs, banks generally need to resort to the secondary money market to satisfy their funding needs. This creates some (imperfect) arbitrage opportunities. For instance, instead of bidding for a reversed repo in an MRO, a bank can also borrow with a one week maturity in the Eurepo market.[10] The quality of collateral required in the Eurepo market is higher than what is needed in the MROs. Alternatively, a bank can also buy a one week Eonia-swap which guarantees a bank the payment of a Eonia-swap interest rate in exchange for receiving the result of capitalizing the Eonia rate for a life span of one week.[11] Thus, it permits a bank to borrow in the overnight market a certain amount without incurring any further interest rate risk. However, this constitutes only an imperfect arbitrage, because (i) banks are not necessarily able to borrow at the Eonia, and (ii) the involved credit, collateral and auction risk differ in an Eonia-swap compared to borrowing in an MRO auction.

In order to contain interest rate fluctuations in the secondary money market within a reasonable range, the ECB provides banks with two additional standing facilities. The marginal lending facility grants banks unlimited access to overnight liquidity at a penalty rate that was 100 basis points above the minimum bid rate in our sample period.[12] When drawing on the marginal lending facility, banks have to provide sufficient collateral meeting the general eligibility criteria for open market operations. At the deposit facility, banks can deposit excess liquidity at a rate which was 100 basis points below the minimum bid rate. Arbitrage opportunities

[10] The Eurepo market refers to the collateralized segment of the euro area money market and constitutes one of the highest trading platforms within the euro area. For further details see http://www.eurepo.org.

[11] In this interest rate swap, as with most swaps, there is no initial or final exchange of principal. The notional principal amount is solely used to determine the two interest rate flows, which in any case are settled via a single net payment at maturity. The European Over-Night Index Average (Eonia) is a reference rate for the overnight segment of the unsecured money market. The Eonia swap market covers roughly 40% of the overall OTC derivatives market, see e. g. European Central Bank (2007a).

[12] Note that although the marginal lending rate is well above the key interest rate, it is well below the penalty rate applied to the reserve deficiencies.

prevent banks from trading central bank liquidity outside the corridor set by these two standing facilities.

2.3 Identification of a Market Demand Function

2.3.1 Data Description: Banks' Bidding Behavior

We have a record of all price-quantity pairs that each German registered financial institution placed in the Eurosystem's MROs during the period June 27, 2000 to October 15, 2008. This data is provided by Deutsche Bundesbank and covers on average 48% of the MROs' aggregate bid and total allotment volume. Among all MRO participants, 67% are German banks. Thus, we have a relatively large snapshot of overall bid-quantity pairs submitted in Eurosystem's MROs.

Until March 2004, banks anticipated future rate cuts of the ECB on several occasions and, therefore, simply refrained from bidding in the MROs, see e. g. Bindseil (2004b). As a result, the ECB could not allot the intended volume of reserves needed for a smooth fulfillment of reserve requirements in the period until the subsequent MRO. This caused severe reserve imbalances in the short-term money market. In order to stop the disturbing strategic bidding behavior of banks, the ECB adjusted its operational framework in March 2004. The MRO maturity was reduced from two to one week and ECB's interest rate decisions were synchronized with the reserve maintenance period, see e. g. European Central Bank (2003). Additionally, the ECB facilitated counterparties' anticipation of its liquidity allotment in the MROs by publishing its assessment of the banking system's liquidity needs that serves as the basis for its allotment policy. As a result of the exacerbated crisis in the post-Lehman period, the ECB switched its MRO auction format from a variable rate tender to a fixed rate auction design with full allotment as of October 2008. In a fixed rate tender with full allotment, every information about the MRO-related refinancing conditions is already pre-announced. This new auction format reveals no information on the banks' willingness to pay as it requires only the submission of the liquidity amount. The interest rate at which liquidity will be provided to MRO participant is pre-announced by the ECB. To account for the structural change stirred by both reforms of the ECB's operational framework as of March 2004 and October 2008, respectively, we select the sample period from March 09, 2004 to October 09, 2008 for our analysis. Furthermore, we will divide the sample into a pre-crisis and crisis period as of August 2007.[13] Within this sample period, we have a total of 240 MRO auctions, i.e. 178 for the pre-crisis and 62 for the crisis period, respectively.

2.3.2 An Empirical Model for Aggregate Liquidity Demand

Some Preliminary Considerations

Before we suggest an appropriate econometric model to derive a market demand function, we first order the reported bids for each auction t. Recall that the tick size is 1 basis point. This allows a discrete and ascending ordering for $i = 1, \dots, n$ distinct rounded yields that emerged from all $j = 1, \dots, m_i$ submissions such that $r_1 \leq r_2 \leq \dots \leq r_n$. Second, we aggregate the liquidity demand of all participants within each ordered yield class i of the respective auction. In a last step, we cumulate this sum of quantities in a way that for each auction t, the collection of i yield classes with the corresponding cumulated quantities, $\sum_{i=1}^{n} \sum_{j=1}^{m_i} L_{ij}^d \geq \sum_{i=2}^{n} \sum_{j=1}^{m_i} L_{ij}^d \geq \dots \geq \sum_{j=1}^{m_1} L_{nj}^d$ form our aggregated bid curve.

To control for the effect of (imperfect) arbitrage opportunities with respect to the secondary money market, we normalize the ordered auction bid classes, r_i, by the one-week Eonia swap rate, $swap^{1w}$. This normalization follows Bindseil et al. (2009) and allows us also to compare bids over time. We use the one-week swap rate as it corresponds to the average short-term interest rate that is expected to prevail over the maturity of the MROs. It is therefore less affected by outliers than the daily Eonia. Because MROs are conducted only once a week, the one-week

[13] Structural breakpoint tests support this date as the start of the financial crisis, see Section 2.6.6 in the appendix.

Eonia swap rate prevailing at the auction's announcement day cannot be affected by expectations about future auction outcomes.[14] The timing of the MROs suggests to use Eonia swap rates prior to the auction day. Hence, we normalize the submitted bids for each auction t as follows:

$$\widetilde{r}_{it} = r_{it} - swap_t^{1w}, \quad t = 1, \ldots, T \tag{2.1}$$

where we use the index t to account for the auctions and i for each ordered yield class along the market demand function. $swap_t^{1w}$ refers to the one-week swap rate that we have observed at the announcement day of auction t, i.e. one day before the repo auction.

For an intertemporal comparison of auctions with different volumes, we will also normalize the aggregate liquidity demand in a way that enables a unified and unit free re-scaling:

$$l_{it}^d = \frac{\text{aggregate liquidity demand}_{it}}{\tilde{L}_t^s}, \tag{2.2}$$

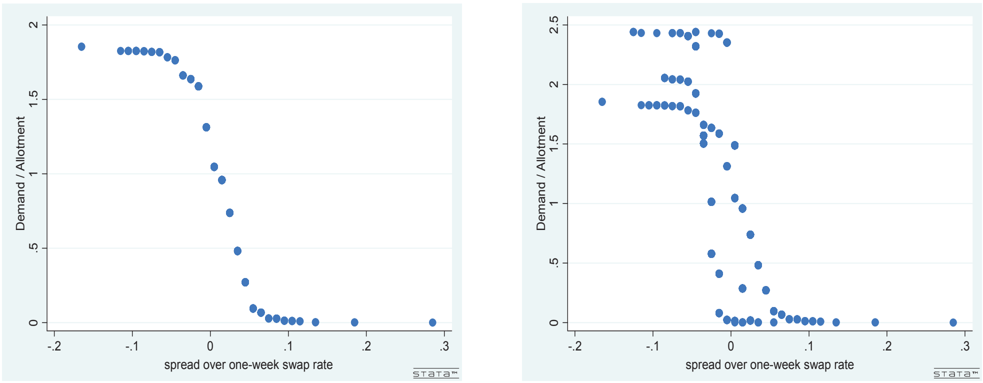
where for each auction t, aggregate liquidity demand at each ordered yield class i is expressed relative to the ECB's aggregate liquidity supply ($\tilde{L}_t^s$). The ECB's total allotment, however, reflects its aggregate liquidity supply to all banks within the euro area (EU). Therefore, we adjust the total allotment for the fraction of German banks (GE) as follows:

$$\tilde{L}_t^s = L_t^s \cdot \frac{\text{cumulative required reserves}_\text{p}^\text{GE}}{\text{cumulative required reserves}_\text{p}^\text{EU}} \tag{2.3}$$

with *p* denoting the respective reserve maintenance period. Note that l_{it}^d is thus a measure for the *excess liquidity demand* or the *disproportional recourse* to Eurosystem's credit.

Figure 1 plots the collection of i price-quantity pairs for one MRO (left figure) and several MRO auctions (right graph) in our sample. Consider the aggregated bid curve for a single MRO auction depicted in the left graph. Each circle represents the cumulative sum of liquidity demand as a fraction of total allotment at the respective yield class in the respective auction.

Figure 1: Some Observed Aggregated Bid Curves

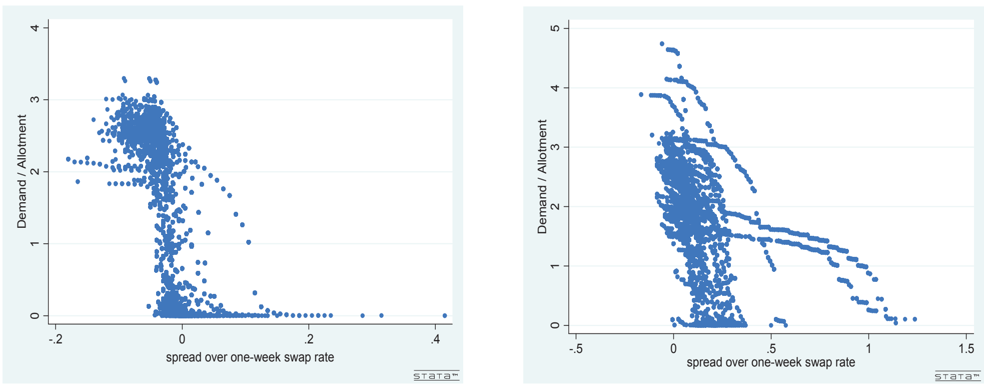


(a) An aggregate bid curve for one MRO

(b) The aggregate bid curves for four MROs

Notes: While the left graph reflects the aggregate bid function of one MRO auction, the right panel shows the bid curves for all MROs conducted in December 2005. Each dot on the respective aggregate bid curve represents the cumulated sum of liquidity demand as a fraction of total liquidity supply for the respective bid rate.

Figure 2: All Observed Aggregated Bid Curves



(a) Aggregate bid curves before August 2007

(b) Aggregate bid curves after August 2007

[14]Alternatively, we used the one-week Eurepo rate. Refer to Section 2.6.3 of the appendix to see that the results remain qualitatively similar.

The form of this observed aggregate bid function shows two horizontal segments at the lower and upper ends and a decreasing part in between. The pattern is initially slightly concave and then convex. These three segments may be interpreted as follows. The upper end shows that above a given quantity the market is not willing to absorb more liquidity even at very low rates. The middle section may imply that due to arbitrage opportunities the vast majority of bids are placed closely around the one-week swap rate.[15] The lower end of the market demand function means that at the auction there is a demand for a certain (small) amount of liquidity, for which some have a relatively high willingness to pay. Despite large fluctuations, we observe this general pattern for all aggregate bid curves in our sample, see Figure 2.

Empirical Model

Following Boukai and Landsberger (1999), we apply the following three-parameter logistic function to model the observed aggregated bid curves:

$$l_{it}^{d} = \frac{\alpha_t}{1 + exp(\frac{(\widetilde{r}_{it} - \tau_t)}{\lambda_t})}, \tag{2.4}$$

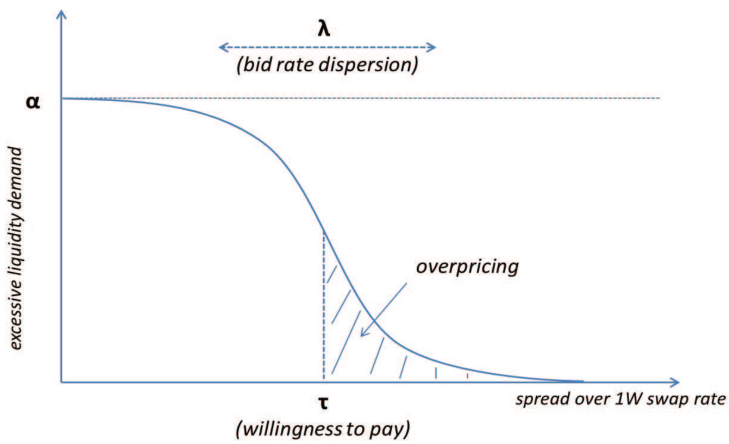
with $\alpha > 0$ and $\lambda > 0$ and where L^d denotes the aggregated liquidity demand (in terms of volume) for each normalized bid rate $\widetilde{r}$. τ may be both negative and positive.[16] The scalars $\widetilde{r}_{it}$ and l_{it}^{d} represent the coordinates of the *i*th observed yield class of auction *t*. The three parameters of our logistic function of auction t are captured by $\theta_t = (\alpha_t, \lambda_t, \tau_t)'$. We do not claim that our specification is the only way to describe the data. In fact, running an *n*th order polynomial may yield better

[15] Mind the differences for our crisis sample. We will discuss this in more detail in the next section.

[16] Alternatively, we allowed for asymmetries around τ. However, the results remained qualitatively the same (not reported, but available on request). This is intuitive since bidders submit a *schedule* of demand functions. Hence, the quantities demanded for average rates should be higher than for extreme rates. It is reasonable to think that bids are concentrated around a mean and that bids are therefore distributed with a single mode. In other words, this can be interpreted as the integral of a bell-shaped density function of interest rates. This would suggest a rather symmetric distribution of bids around the inflexion point.

results. However, the usage of the logistic curve has various advantages.[17] First, it is flexible as it captures both the convex and concave features of the demand function observed in our data, see Figure 2. Second, it describes the price-quantity relationship with only three parameters. Third, as will be shown below, the fit is quite astonishing. Fourth and most importantly, however, these parameters allow for economically highly relevant interpretations, see also Preget and Waelbroeck (2005). Figure 3 illustrates our three parameters of the market demand function.

Figure 3: Logistic Market Bid Function



α represents the *market satiation level*, beyond which there is no demand for central bank liquidity in the primary market "regardless" of its price. Obviously, potential bids have a lower bound since submissions below the minimum bid rate are not considered. Hence, a is the asymptotic value of L^d as r approaches the lowest bid allowed, i.e. the minimum bid rate. Roughly speaking, it is the height of the almost horizontal segment at the beginning of the curve. Since all volumes are set equal to 1, the parameter $\alpha - 1$ may also be interpreted as the magnitude of unsatisfied liquidity demand.

The parameter τ determines the location of the market demand function and hence measures the position of the bids relative to the secondary money market rate. Due

[17] The general properties of the logistic curve are well described in Balakrishnan et al. (2006).

to the logistic specification, τ reflects the (unique) inflexion point of our market demand function that happens to be the value of $\widetilde{r}$ at which the market reaches half of its satiation level, i.e. $\frac{a}{2}$. This parameter may therefore reveal the *willingness to pay* or the *degree of overpricing*.

λ, as the scale parameter, measures the *dispersion of the bids* around τ. A larger amount of uncertainty leads to more dispersed bids and thus to a higher λ. Furthermore, this parameter is closely linked to the price elasticity of reserve demand, see Appendix for further details.

To estimate Equation (2.4), we apply the method of non-linear least squares that minimizes the sum of squared residuals. As starting values for the iterative algorithm, we use the estimates of a linear transformation of the logistic function in (2.4). This ensures the convergence of the minimization algorithm to a global minimum. Hence, these preliminary parameter estimates are obtained as follows

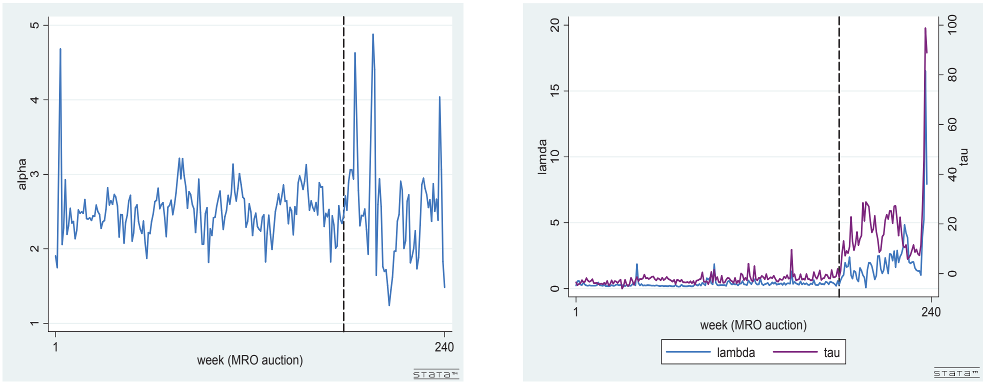
$$log(\alpha_t - 1) = -\frac{\tau_t}{\lambda_t} + \frac{1}{\lambda_t}\widetilde{r}_{it} + \varepsilon_{it}, \qquad (2.5)$$

To use this specification, however, we must assign a value to α. Following Preget and Waelbroeck (2005), we use the highest observation for each auction. However, to avoid division by zero, we use exactly 101% of this value. We can then estimate parameters $\beta_{1t} = -\frac{\tau_t}{\lambda_t}$ and $\beta_{2t} = \frac{1}{\lambda_t}$ for each auction by the ordinary least squares method. Note that this approach only allows for the determination of the initial values of two parameters of the logistic curve: $\widehat{\lambda}_t = \frac{1}{\widehat{\beta}_{2t}}$ and $\widehat{\tau}_t = -\frac{\widehat{\beta}_{1t}}{\widehat{\beta}_{2t}}$.

2.3.3 Identification of a Market Demand Function: Empirical Results

Figure 4a presents our estimates of α for each auction as of March 2004. It shows that before August 2007 our point estimates of α vary roughly between 2 and 3, i.e. German banks' satiation is twofold and threefold higher than the level required to fulfill liquidity needs. During the crisis, the span within which excessive liquidity demand fluctuates widens. However, Table 1 reveals that the average factor remains at roughly 2.5. Furthermore, $\hat{\alpha}$ shows large across-auction fluctuations implying that excessive liquidity demand varies across auctions.

Figure 4: Estimation of Model Parameters



(a) Estimation of the excess liquidity demand α

(b) Estimation of the bid rate dispersion λ and the willingness to pay τ

Table 1: Summary Statistics: Parameter Estimates

Parameter estimates	Units	Mean	Std	Min	Max
09 Mar 2004 - 31 Jul 2007: 178 auctions					
$\widehat{\alpha}$		2.49	0.27	1.75	3.21
$\widehat{\lambda}$		0.35	0.22	0.15	1.85
$\widehat{\tau}$	bp	-2.29	1.72	-6.04	9.69
08 Aug 2007 - 09 Oct 2008: 62 auctions					
$\widehat{\alpha}$		2.51	0.75	1.24	4.88
$\widehat{\lambda}$		2.41	2.88	0.07	16.59
$\widehat{\tau}$	bp	18.35	16.43	-1.41	98.63

Notes: The table refers to Equation (2.4). $\hat{\alpha}$ denotes the estimated aggregate liquidity demand relative to total reserve requirements of the German banking sector such that $\hat{\alpha} - 1$ reflects the estimated magnitude of unsatisfied (excessive) demand. Note that we have multiplied both $\hat{\lambda}$ and $\hat{\tau}$ by 100.

Figure 4b reflects the estimates of λ and τ for all 240 auctions. Prior to the crisis, the estimates for λ show an average dispersion value close to zero.[18] The figure

[18]For illustration reasons we have multiplied λ and τ by 100.

reveals that German banks placed their bids very close around the one-week swap rate. After the onset of the crisis, however, bids became increasingly dispersed around their swap rate counterpart. According to Table 1, there is on average a sevenfold increase of bid rate dispersion relative to the pre-crisis sample.

A similar pattern can be observed for the location parameter τ. Before the crisis, $\hat{\tau}$ moves moderately close to zero. In that sense, the estimates of τ show the close link between the one-week swap rate and the price for liquidity in the primary money market. The average inflexion point of a typical market demand function is at -2 basis points. That is, the typical willingness to pay for liquidity in the ECB's auctions is on average 2 basis points lower than in the secondary money market. During the crisis, however, banks are typically willing to settle for prices that deviate on average more than 18 basis points from secondary money market prices.

2.3.4 Discussion of Results

The fact that banks demand on average more reserves than they need to smoothly fulfill their requirements may imply that participating German banks bid rather as a buy-and-sell strategy than with the incentive to buy and keep most of their liquidity locked in their portfolios. This conjecture may be derived from the following consideration. To contain the opportunity costs, euro area banks have two alternative strategies to deal with their excess reserves: (i) they may either park their liquidity surplus in the Eurosystem's deposit facility or (ii) lend it in the secondary money market. Before October 2008, however, euro area banks' recourse to the deposit facility was rather of negligible amount, see e. g. Heider et al. (2010). Hence, there is reason to believe that German banks lend their excess funding in the secondary money market.

Larger fluctuations of $\hat{\alpha}$ throughout the crisis period are consistent with anecdotal evidence that German banks had a stronger preference to over-satisfy their liquidity needs at an early stage of the reserve maintenance period. In order to respond to this change in banks' liquidity demand pattern, the ECB started to allot significant excess liquidity at the beginning of the maintenance period during the crisis. This excess liquidity was then gradually reabsorbed over the remaining weeks of the period by reducing the allotment above the benchmark. On average, banks still continued to have a liquidity surplus close to zero at the end of each period as before August 2007, see e. g. European Central Bank (2010). This might explain why both the lower (min) and upper (max) end of the fluctuation range has changed.

The estimation results obtained for λ indicate that the secondary money market plays a pivotal role in banks' bidding behavior. Before the crisis, German banks were willing to settle for yields that deviate only slightly from interbank money market rates. In fact, this "rigidity" around zero may imply that the swap market is indeed perceived as a fairly good substitute for the primary money market by German banks. In other words, before August 2007 swap rates represented very well the yields that the German bidders could get if they traded on the secondary money markets instead of at the auction. Therefore, there was no reason for these financial institutions to deviate significantly from secondary money market rates when they bid at the MROs. For the period after August 2007, however, our results change substantially. The lower part of Table 1 shows that not only bids vary among German banks (mean) at each auction but also across banks across auctions (standard deviation). This observation suggests that different German banks faced different funding conditions in the secondary money market.

Similar interpretations may be drawn for our estimations of τ. While we observe an average underpricing of central bank liquidity in the primary money market before August 2007, the German banking sector has a significantly higher willingness to pay during the crisis. The empirical literature identifies the volatility of bond returns as the key driver for bank's bidding behavior and underpricing, see Nyborg et al. (2002), and Keloharju et al. (2005). These papers find that when volatility increases, the typical bidder tends to reduce the average price at which he bids, lowers his total demand, and increases the dispersion of his bids. Their evidence also suggests that the dominating element behind the observed behavior and underpricing is that bidders have private information and adjust rationally for the champion's plague.[19]

However, all these conjectures need a further elaboration. Therefore, we will devote the next part of our exercise to the identification of potential determinants that shape the three parameters of our aggregate liquidity demand. For this purpose, we relate the effects and determinants raised in the literature to specific variables in order to assess the explanatory power of the different theories. Our analysis will substantially benefit from our data set that we obtained from the Deutsche Bundesbank.

2.4 The Determinants of Market Demand for Liquidity

2.4.1 Data Description

We have data on reserves from every German registered financial institution in the period January 2004 to October 2008 that was required to hold central bank reserves with the Eurosystem. In total, we are able to capture daily reserve data on 1975 German financial institutions as of January 2004. The reserve data includes (i) each institution's cumulative reserve holdings of each day during the respective maintenance period, (ii) the bank's marginal reserve holdings at the end of each business day, and (iii) each institution's reserve requirements for each maintenance period. We consider each bank that has bid at least once in the ECB's MROs as a bidder. In the same vein, we identify 1067 out of the 1975 German financial institutions as MRO bidders during our sample.

Additionally, we have each bank's end-of-month balance sheet data as it is collected by Deutsche Bundesbank within the scope of its bank balance sheet statistic

[19] For the discriminatory auction mechanism, Ausubel (2004) has suggested the terminology *champion's plague* instead of the winner's curse, to emphasize that the more units a bidder wins, the worse news it is.

survey. All German banks are required to contribute to this poll on a monthly basis. For all the banks in our sample, we obtain balance sheet data as of the last calendar day of each month. The data covers each bank's balance sheet position for the period January 1999 through December 2008.[20]

Based on unique bank codes, we are able to merge these data sets with the data on banks' bidding behavior from above. For our analysis we will adopt the same sample period as above. Thus, as of March 2004 we have data on 57 end-of-month balance sheet statistics. Neither the data on reserves nor the results of the balance sheet survey are publicly available. To the best of our knowledge, this is the first time that these data are jointly used. The variables that we will derive from these data will be motivated by economic theory as we will discuss in the next section.

2.4.2 Variables and Hypotheses

Interbank Market Frictions

Financial institutions can either seek funding from the primary or the secondary money market to fulfill their liquidity needs. This creates a scope for arbitrage opportunities between these two markets, which in turn may induce frictions.

One major friction is that the interbank money market is not a fully competitive market. Banks might gain market power in the secondary money market because the amount of reserves available in the market is predetermined by the central bank's liquidity allotment.[21] Thus, individual banks can try to corner the market, ration liquidity supply and squeeze liquidity-short banks. The ability of individual banks to follow that strategy depends on the distribution of excess reserve holdings in the banking sector. That is, the more concentrated excess reserve holdings

[20]Further details and an overview of the complete balance sheet data is available on www.bundesbank.de/meldewesen/mw_formbankenstatistik_bilanzmfi.en.php.

[21]Note that the liquidity neutral allotment policy of the ECB generates a cash-in-the-market constraint. There are a number of theoretical contributions showing that such a cash-in-the-market constraint might induce market power in the secondary money market, see e. g. Fecht and Hakenes (2006) and Acharya et al. (2008).

are, the larger is individual banks' market power.[22] As a consequence, banks that rely on the secondary money market to satisfy their liquidity needs run the risk of paying excessive rates, in particular when reserve holdings are asymmetrically distributed. This fear of being squeezed is what Simon (1994) labels the *loser's nightmare*. Nyborg and Strebulaev (2004) show within a theoretical model that the fear of market squeezes leads to more aggressive bidding behavior in the Eurosystem's repo auctions.

Imperfect information in financial markets creates a second interbank money market friction. This is because bank-specific liquidity shocks are unobservable and because banks cannot monitor each other's balance sheets. As pointed out by Bhattacharya and Gale (1987), this informational asymmetry generates an incentive for banks to cover not only their idiosyncratic liquidity shocks, but also to refinance their average liquidity needs in the interbank market. Banks under-invest in reserve holdings because long-term investments usually have a higher expected yield than liquidity holdings. Thus, banks try to save on these opportunity costs by reducing their precautionary liquidity holdings and expect to manage their liquidity needs with excess liquidity offered by other banks in the secondary money market. Among German banks, individual savings banks and cooperatives may free-ride on the efforts of their head institutions, ultimately proving costly for them, see Fecht et al. (2011).[23] In equilibrium, this under-investment in liquidity leads to an excessively high interbank money market rate, i.e. the arbitrage-free interbank rate exceeds the welfare optimal rate.[24] An excessively high secondary money market rate, however, involves particularly large inefficien-

[22]Recall that this stems from the fact that liquidity is tight in the euro area banking sector. That is, if one bank has more than it needs, another must have less.

[23]For an earlier discussion of the free-rider problem within alliances see Olson Jr. and Zeckhauser (1966).

[24]This is, for instance, pointed out by Allen et al. (2009) who argue that it is the central bank's role to correct for that under-investment in liquidity by increasing the supply of reserves through open market operations and bring down the money market rate to its optimal level.

cies if the need for liquidity reallocation is high.[25] The larger the asymmetry in liquidity holdings in the interbank money market, the larger is the need for a reallocation. This increases the costs of the excessively high secondary money market rate for liquidity-short banks and thereby the costs of this friction. Consequently, if reserves are very unevenly distributed in the banking sector, banks' willingness to pay for reserves in the primary money market should be higher. As a strategy to protect themselves, banks may disperse their bids while bidding aggressively. Both theoretical arguments lead us to the first empirically testable hypothesis:

Hypothesis 1 *A larger dispersion of reserve holdings in the banking sector increases banks' willingness to pay (τ), banks' bid rate dispersion (λ), and their excessive liquidity demand (α).*

In order to test this hypothesis we use our data on banks' reserves. We determine the variable *remaining required reserves* for each bank b in our sample immediately before the auction t, i.e. on the announcement day, such that

$$\text{remaining required reserves}_{btp} = \frac{\text{total required reserves}_{bp} - \text{cumulative holding}_{btp}}{\text{days left of maintenance period}_{btp}}, \quad (2.6)$$

where p denotes the respective reserve maintenance period. This measure reflects what each bank needs to hold from auction t's perspective on a daily basis to exactly fulfill its requirements within the ongoing maintenance period. To account for the heterogeneity in liquidity needs among all German banks, we further compute the *standard deviation* across all banks' remaining required reserves on the announcement day of auction t within period p.

Intuitively, as the reserve requirements become binding towards the end of the reserve maintenance period, the potential for market squeezes increases and thus the fear of market squeezes should also become more apparent. Moreover, at the beginning of a maintenance period, banks might hope for an offsetting liquidity shock in the course of the maintenance period that balances a given underfulfillment. To see this, consider an event of a positive liquidity shock that causes

[25]In fact, Freixas et al. (2010) assert that the central bank's need to stabilize interbank money market rates increases under more dispersed liquidity holdings in the banking sector.

banks' accounts to exceed the remaining part of their reserve requirements for the respective maintenance period. Any reserves held in excess of the required amount must then be parked at the deposit rate, which is substantially lower than the money market rate. Since this would be more expensive, these banks have an incentive to keep their accounts before the (potential) shock realizes at an appropriate level, see e. g. Pérez Quirós and Rodríguez Mendizábal (2006). Towards the end of the maintenance period such an offsetting liquidity shock becomes rather unlikely and banks need to balance the under-fulfillment through a money market transaction. Thus, during the last days of the maintenance period also the second friction becomes more relevant and banks become more worried about a general mark-up charged in the interbank money market. Therefore, for a given heterogeneity in reserve holdings, banks should bid more aggressively towards the end of the maintenance period. Hence, we expect a higher willingness to pay (τ), higher bid dispersion (λ) and higher quantities demanded (α) as the end of the reserve maintenance period approaches. When banks, however, develop a strong preference to (over-)satisfy their liquidity needs at an early stage in the maintenance period, we would expect that increasing heterogeneity in reserve balances should also affect the shape of aggregated bid curves within the maintenance period.

A third type of friction in the interbank money market results from asymmetric information about counterparties' credit risk. Following Akerlof's path-breaking work, Freixas and Jorge (2008) show that unobservable credit quality of counterparties leads to an adverse selection problem in the unsecured interbank market, i.e. a pooling equilibrium characterized by credit rationing. Thus, the risk premium charged is too high for the default risk of low risk borrowers – they pay an additional lemons premium – while it is too low for high risk borrowers. If the fraction of low quality borrowers increases, the overall risk premium will rise. Hence, the lemons premium paid by high quality borrowers increases as well. Eventually good borrowers drop out of the secondary money market, satisfying their liquidity needs elsewhere, e. g. by liquidation of long-term investments, and leave an adverse selection of low quality borrowers in the money market. Due to this adverse selection effect the default risk in the interbank money market increases further leading to an even higher risk premium being charged. In order to circumvent the negative externalities attached to the adverse selection effect within the interbank money market, banks with excess liquidity in the market will find it beneficial to ration their liquidity supply, in analogy to Stiglitz and Weiss (1981). In any case, liquidity-short banks find it more costly or more difficult to refinance in the secondary money market the more severe the adverse selection problem is. Thus, those banks will use the Eurosystem's repo auctions more intensely and bid more aggressively. Heider et al. (2010), for instance, show that the adverse selection effect worsens when the difference in the default probabilities between high and low quality borrowers in the interbank money market becomes larger or, more generally, the more heterogenous default probabilities are in the banking sector. Consequently, a higher discrepancy in the banks' default probabilities should also increase banks' participation and willingness to pay in the ECB's MROs. This rationale leads us to the second hypothesis we aim to test:

Hypothesis 2 *A larger dispersion of credit risk in the banking sector raises banks' overall demand (α), the willingness to pay for central bank reserves in the auctions (τ), and encourages bid dispersion (λ).*

In order to test this hypothesis we require a measure for the heterogeneity of banks' default probabilities. As commonly applied, we could use credit default swaps or credit ratings for those banks for which those figures are available. However, those credit risk indicators are publicly available information. Thus the dispersion of these indicators across the banking sector does not measure the severity of adverse selection problems in the interbank money market.

We rather use our access to the monthly balance sheet statistic to derive a measure for bank's credit risk.[26] Equity, in general, meets the most straightforward, narrow definition of capital as funds cannot easily be withdrawn. The sum of total assets denotes the simplest measure of bank size, even though it excludes off-balance sheet activities. The ratio between both measures, i.e. the *equity ratio*, captures a component of individual bank's solvency risk that is subject to asymmetric in-

[26] Recall that on an individual bank basis, this end-of-month information is only available to the Deutsche Bundesbank.

formation. Additionally, the equity ratio plays a crucial role in the bank's credit rating and is also related to each bank's cost of raising funding in the secondary money market. In contrast to other proxies for credit risk, the equity ratio is a completely transparent measure. For our analysis, we classify the sum of subscribed capital and reserves less published losses from each bank's balance sheet as the bank specific equity variable.[27]

It is reasonable to assume that money market participants have some notion whether the dispersion of the equity ratio and thus the solvency risk in the banking sector increased or decreased. Thus, we will use the *standard deviation* of the equity ratio across German banks to capture whether adverse selection in the interbank money market became more or less severe from the perspective of market participants.

Banks that are rationed in the interbank money market rely to a larger extent on the primary money market to cover their liquidity needs to balance out liquidity shocks. A persistent recourse to the primary money market might also be seen as an indication that a bank cannot refinance in the secondary money market. Thus, a higher fraction of banks that persistently participate in the ECB's MROs might reflect rationing in the interbank money market. According to this argument a higher fraction of persistent bidders in the MROs should also be accompanied by a higher level of reserve demand combined with a more aggressive bidding behavior observed in the ECB's repo auctions. This idea yields to a further testable hypothesis:

Hypothesis 3 *A larger share of persistent bidders in the MROs shifts banks' overall reserve demand (α) upward and increases their willingness to pay for central bank reserves in the auctions (τ).*

In order to test this hypothesis we define a bank to be a persistent bidder if it participated in more than 90% of the preceding auctions from auction t's perspective. In particular, we use an updating approach to determine the fraction of persistent bidders such that at auction t, our variable "persistent banks" refers to all auctions

[27]The capital of foreign subsidiaries of domestic banks is also included in this measure.

up to $t-1$. Our variable "persistent banks" then denotes the fraction of those banks persistently bidding in MRO's relative to all participating banks.

Market Liquidity and Funding Liquidity

Banks may use the general financial market as an alternative liquidity source. Selling off assets also allows banks to cover their liquidity needs. But under asymmetric information, long-term assets can only be liquidated at a discount.[28] The extent of this discount depends on the ability of market makers and informed traders to absorb these asset sales. The more liquidity constrained market makers are, the higher is their bid-ask spread as for instance argued by Brunnermeier and Pedersen (2009).[29] The more financially constrained informed traders (e.g. institutional investors) are, the lower is the price elasticity of asset demand, the stronger is the effect of a cash-in-the-market pricing, and the larger are price fluctuations from given asset sales as pointed out e. g. by Allen and Gale (1994). In any case, the expected loss incurred by a bank that aims to cover its liquidity needs through asset sales is higher, the lower asset market liquidity is and thus the higher is asset price volatility. As a consequence, banks' preference to liquidate their assets is lower for highly volatile asset prices. This also means that banks' dependency on the primary money market increases for a higher asset price volatility. We therefore conclude that under the occurrence of high asset price volatility banks should bid for larger amounts and at higher rates in the ECB's repo auctions. Furthermore, as a reallocation of liquidity through the asset market becomes more costly, banks' incentives for precautionary liquidity holdings should increase leading to a higher overall demand for central bank reserves. This, in particular, captures the main reasoning of Allen and Gale (1994). Our fourth empirically testable prediction is therefore as follows:

[28] When banks sell off their assets in need for reserves they act as liquidity traders in the market. Therefore, they bear on average a loss when selling off their assets to informed market participants, see e. g. Freixas and Jorge (2008).

[29] See e. g. Benston and Hagerman (1974), Grossman and Miller (1988), Glosten and Milgrom (1985), and Kyle (1985) for standard references on market micro structure.

Hypothesis 4 *In times of low market liquidity and volatile asset prices banks' willingness to pay for reserves (τ) as well as the aggregate reserve demand (α) in the primary money market increase.*

Empirically, we use the log of the Vstoxx as a measure for asset price volatility. The Vstoxx is an index for the Euro Stoxx 50 implied volatility and comprises the largest 50 euro area listed firms. It is derived from the expected volatility for the future Euro Stoxx 50 prices implied by the respective stock option prices and thus captures market participants' expected stock price volatility over the next 30 days rather than the realized volatility.

Apart from financial market liquidity that affects banks' costs when assets are sold under distress, banks' asset structure might also restrain banks' ability to tap financial markets in search for liquidity. The lower the stock of tradable assets that banks hold on the balance sheets, the lower is the ability of banks to sell off these assets on short notice and thereby attract liquidity. As a consequence, banks are again more dependent on the liquidity provision in the primary money market and will bid more aggressively in the ECB's MROs. Moreover, banks might have stronger incentives for precautionary liquidity holdings, which should increase the level of aggregate reserve demand. Similarly, a high share of long-term assets on banks' balance sheets should reduce under asymmetric information banks' ability to refinance liquidity shortages through asset sales. In addition, a high maturity mismatch in the banking sector increases banks' need to roll-over liabilities and thus raises banks' sensitivity to changing market conditions in secondary money markets. A high level of maturity mismatch increases banks' liquidity risk and the vulnerability to potential liquidity shortages, see e. g. Brunnermeier (2009). All in all, a larger maturity risk carried on banks' balance sheets should lead to a more aggressive bidding and a larger aggregate reserve demand in the ECB's open market operations.

Hypothesis 5 *The lower the fraction of marketable assets and the larger the maturity mismatch on banks' balance sheets, the more dependent banks are on the primary money market. Hence, banks have a higher liquidity demand (α) in central bank auctions and bid more aggressively (τ).*

To test this hypothesis, we use again items from the balance sheet statistic that we obtained from the Deutsche Bundesbank. As tradable assets, for instance, we classify debt instruments, shares, and other variable-yield securities. To account for the average share of tradable assets in the German banking sector, we compute the ratio between tradable assets and balance sheet total across all banks.

To account for the average maturity mismatch in the German banking sector, we follow the approach of Deep and Schaefer (2004) and Berger and Bouwman (2009). We measure maturity mismatch as the sum of bank's long-term assets and short-term liabilities over its equity. We determine this measure as an average over all financial institutions. We categorize liabilities (both to banks and non-banks) with a maturity of up to one year and savings deposits of non-banks at a period of notice up to 3 months as short-term liabilities. As long-term assets we define loans and advances both to banks and non-banks beyond the one-year maturity. Table 2 summarizes the expected response of our parameter estimates, $\hat{\alpha}, \hat{\lambda}, \hat{\tau}$, to variables derived from economic theory.

Table 2: Theoretical Predictions on the Determinants of Aggregate Liquidity Demand

		$\hat{\alpha}$	$\hat{\lambda}$	$\hat{\tau}$
Remaining Required Reserves	(std)	+	+	+
Equity Ratio	(std)	+	+	+
Persistent Banks	(%)	+	+/−	+
Vstoxx	(log)	+	+/−	+
Maturity Mismatch	(%)	+	+/−	+
Tradable-to-Total-Assets	(%)	−	+/−	−

2.4.3 Empirical Model

To test the hypotheses derived from the theoretical literature, we apply the following ordinary least square regression[30]:

$$\begin{aligned}\widehat{\theta_t} &= c + \alpha_1 D_t^{lw}\text{Res}_t + \alpha_2(1-D_t^{lw})\text{Res}_t + \alpha_3 EQR_t + \alpha_4 PB_t \\ &+ \alpha_5 Vstoxx_t + \alpha_6 MatMis_t + \alpha_7 TA_t + \beta' X_t + \upsilon_t \qquad (2.7)\end{aligned}$$

where $\widehat{\theta_t}$ comprises the estimated parameters $\hat{\alpha_t}$, $\hat{\lambda}_t$, and $\hat{\tau}_t$ for each auction t. We estimate this equation by equation. Note that our analysis refers to MROs that are performed weekly, i.e. t denotes a weekly time structure. υ is assumed to have a zero mean and *i.i.d.* characteristics. As discussed above, our right-hand side variables correspond to the standard deviation across banks' remaining required reserves (Res), the standard deviation across banks' equity ratios (EQR), the share of persistent banks (PB), the log of Vstoxx ($Vstoxx$), the average maturity mismatch prevailing in the banking sector ($MatMis$), and the across banks' mean of tradable assets over balance sheet total (TA) at auction t. D^{lw} refers to a dummy variable that is one for the last MRO conducted during the respective maintenance period and zero otherwise. Furthermore, the vector X includes an end-of-year dummy that is one for the last MRO auction within a year and zero otherwise. In addition, X comprises the autoregressive component of the respective parameter up to the fourth lag.[31]

Generally, we would expect the impact of all our derived variables to be of a non-linear nature. This is in particular the case for the effects stemming from interbank money market frictions and from the illiquidity in financial markets where both influences mutually reinforce each other. Unfortunately, it is not possible to capture

[30]Following the Gauss-Markov theorem, generalized least square estimation would be more efficient than OLS when the system errors are correlated. This could be accounted for by using Zellner's seemingly unrelated regression model. However, Kruskal's theorem (Kruskal, 1968) describes that this efficiency gain disappears when each equation contains exactly the same set of regressors on the right-hand side as in our case.

[31]Since there are on average four MRO auctions during a reserve maintenance period, a lag order of four auctions seems reasonable. This is also suggested by the AIC information criteria.

each facet of the potentially prevailing (feedback) effects in our empirical analysis. However, by investigating the explanatory power of the different hypotheses before and during the crisis period separately, we aim to catch most of these effects. Since financial market tensions were generally more prevalent during the crisis, we would expect that, due to the presumed non-linearities, our hypotheses should turn out to play an empirically more pronounced role after August 2007.

Note that all our right-hand side variables are pre-determined. We use the data on the announcement day, i.e. one day before the auction is conducted, to avoid endogeneity problems. For the balance sheet data, we use the end-of-month entries that are valid before the respective MRO auction t. For instance, the entry relevant for all MROs within September 2005 is provided by the balance sheet statistic on August 31, 2005. To make sure that our results are not driven by the Lehman event, we have excluded all MROs conducted after September 15, 2008.

Empirical Results for the Pre-crisis Period

Table 3 presents the results of our estimation. In the pre-crisis sample, the estimates indicate a significant and plausibly signed response of all three parameters to reserve imbalances, only during the last week of the reserve maintenance period. In that sense, our results are in line with Hypothesis 1. According to our estimates, a change in the heterogeneity of reserve balances at the last-week-operation increases $\hat{\alpha}$ by 0.12 ($0.021 \cdot 1.523/0.27$) standard deviations. Our results also suggest that greater asymmetry in remaining required reserves is associated with higher willingness to pay. A change of these reserve imbalances by one standard deviation will increase the typical willingness to pay during the last week by roughly 1.2 basis points ($(0.021 \cdot 0.549)$) further. The bid rate dispersion, $\hat{\lambda}$, appears to rise also with higher degree of reserve imbalances among market participants during the last week. A change of the asymmetry in remaining required reserves by one standard deviation increases bid shading by roughly 0.54 ($0.021 \cdot 0.057/0.0022$) standard deviations, see also Table 1.[32]

[32]Recall that both λ and τ were multiplied by 100. Our estimates presented in Table 3, however, refer to the initial unit of λ and τ.

Table 3: Determinants of the Aggregate Bid Curve

Variable		Hypothesis	Shape of Aggregate Bid Curve $\hat{\theta}_t = (\hat{\alpha}_t, \hat{\lambda}_t, \hat{\tau}_t)'$ Pre-Crisis: 09 Mar 2004 - 31 Jul 2007 $\hat{\alpha}$	$\hat{\lambda}$	$\hat{\tau}$	Crisis: 08 Aug 2007 - 09 Sep 2008 $\hat{\alpha}$	$\hat{\lambda}$	$\hat{\tau}$
Remaining Required Reserves	(std)	$\mathcal{H}1$						
*Dummy (last week operation)			1.523***	0.057***	0.549***	−0.989	−0.192	−1.115
			(4.11)	(4.17)	(4.55)	(0.67)	(0.98)	(1.05)
*[1 - Dummy (last week operation)]			−0.431	0.010**	0.049	1.001	0.008	0.742**
			(0.58)	(2.16)	(0.89)	(0.44)	(0.21)	(2.27)
Equity Ratio	(std)	$\mathcal{H}2$	−4.056	−0.001	−0.152	−12.119	1.416**	8.897**
			(0.56)	(0.23)	(0.54)	(0.62)	(2.10)	(2.23)
Persistent Banks	(%)	$\mathcal{H}3$	1.480	−0.495	3.221	0.084***	−0.012**	−6.891
			(1.33)	(1.01)	(1.21)	(2.91)	(2.02)	(0.91)
Vstoxx	(log)	$\mathcal{H}4$	−0.22	−0.001	−0.001	0.811**	0.041	0.291***
			(1.20)	(0.64)	(0.37)	(2.45)	(1.18)	(3.63)
Maturity Mismatch	(%)	$\mathcal{H}5$	0.119***	0.001	0.005**	0.294**	−0.001	0.028***
			(2.81)	(0.78)	(2.22)	(2.31)	(0.37)	(2.76)
Tradable-to-Total Assets	(%)	$\mathcal{H}5$	−0.124**	0.001**	0.007	0.795	−1.173	−0.031***
			(2.51)	(2.05)	(0.54)	(0.83)	(0.74)	(3.22)
$\sum_{l=1}^{4} AR(l)$			0.601***	0.234**	0.553***	0.324**	0.167*	0.910***
			(7.92)	(2.34)	(6.97)	(2.01)	(1.83)	(4.45)
Dummy (last week operation)			0.797***	0.005***	−0.031***	0.341	0.039	0.250**
			(2.75)	(3.28)	(2.73)	(0.86)	(1.11)	(2.37)
Dummy (end of year)			−1.101***	0.021***	0.043***	0.840***	0.145***	0.181***
			(7.62)	(24.38)	(3.87)	(2.96)	(3.07)	(3.77)
cons			1.682**	0.004	−0.032	2.989	0.027	−0.072***
			(1.97)	(0.92)	(1.03)	(0.53)	(0.78)	(2.98)
R^2			0.68	0.76	0.71	0.70	0.54	0.86
Obs.				178			57	

Notes: $\hat{\alpha}$ denotes the market's satiation level, $\hat{\lambda}$ measures the bid rate dispersion and is closely linked to the price elasticity of demand. $\hat{\tau}$ captures the typical willingness to pay. The estimated model is presented in Equation (2.7). ***,**,* indicate significance at the 1%, 5%, 10% level. Newey-West HAC consistent t-statistics in parentheses. The index t refers to the weekly MROs during the period March 9, 2004 to September 9, 2008. For this analysis, we have excluded all MROs conducted after September 15, 2008 to make sure that our results are not driven by the Lehman-event. Additionally, we dropped the extraordinary MRO auction (with 2-week maturity and immense liquidity provision) of December 18, 2007. *last week operation* is a dummy variable that is one for the last MRO conducted during the respective maintenance period and zero otherwise. Similarly, we have computed a dummy for end-of-year effects that is always one for the last MRO within a year and zero otherwise. The results presented in the first and second row refer to the interaction of our variable *remaining required reserves* and the dummy(last week operation) and [1-dummy(last week operation)], respectively.

During the rest of the maintenance period, reserve imbalances among banks tend to influence only banks' bid shading behavior. A one standard deviation rise of the asymmetry increases $\hat{\lambda}$ by 0.10 standard deviations. These results indicate that banks' fear of potential market squeezes becomes more apparent as the end of the maintenance period approaches, i.e. when reserve requirements become binding.

The results obtained for the average share of tradable to total assets is also in line with our predictions in Hypothesis 5. According to our estimates, an increase in the ratio between tradable assets and total assets by one percentage point will reduce $\hat{\alpha}$ by 0.46 standard deviations. A further plausible and significant result is obtained for $\hat{\lambda}$. The estimate suggests a rise of 0.5 standard deviations in $\hat{\lambda}$ when the ratio of tradable-to-total-assets increases by one percentage point. Before the crisis, the level of maturity mismatch in the German banking sector affects $\hat{\alpha}$ and $\hat{\tau}$. An increase in the maturity mismatch by one percentage point will increase $\hat{\alpha}$ by 0.16 standard deviations and $\hat{\tau}$ by 0.5 basis points. We find no evidence that further variables affect the shape of a typical aggregated bid curve before August 2007.

Table 4: Summary Statistics: Right-Hand-Side Variables

Before vs. After 08 August 2007					
		Mean		Std	
		before	after	before	after
Remaining Required Reserves	(std)	0.104	0.110	0.021	0.044
Equity Ratio	(std)	0.067	0.077	0.002	0.004
Persistent Banks	(%)	35.465	35.557	3.302	8.253
Vstoxx	(log)	2.795	3.223	0.192	0.201
Maturity Mismatch	(%)	141.38	163.24	35.21	40.02
Tradable-to-Total-Assets	(%)	20.43	18.90	0.40	0.36

Empirical Results for the Crisis Period

For the crisis period, our results are shown in the right panel of Table 3. In line with Hypothesis 1, we find that large reserve imbalances increase banks' willingness to pay. However, our estimates for the crisis period differ from those obtained for the pre-crisis period in one important aspect. While the heterogeneity played a significant role only for the last week auction before August 2007, banks' asymmetry in remaining required reserves affects market's willingness to pay, $\hat{\tau}$, in the MRO before the last auction within the respective maintenance period, after August 2007. The impact of a standard deviation change in banks' reserve imbalances increases the typical willingness to pay in these auctions by 3.3 basis points. This finding is consistent with the anecdotal evidence that after the onset of the crisis banks had a strong preference to (over-)satisfy their liquidity needs before the end of the maintenance period approaches. It is, however, puzzling that there is no empirical evidence for an impact on $\hat{\lambda}$ and $\hat{\alpha}$.

During the crisis, a rise of the heterogeneity by the same order of magnitude is also found to induce more dispersed bids around the respective typical inflexion point. For instance, our estimated coefficient suggests that an increase by one standard deviation of the dispersion of bank's equity assets ratio rises $\hat{\lambda}$ by 0.20 standard deviations. A large heterogeneity in banks' equity ratio pushes also $\hat{\tau}$ upward. This result is in favor of our second prediction as it provides evidence for more aggressive bidding behavior as a result of counterparty risk combined with asymmetric information about it. Following our estimates, an increase in the heterogeneity among bank's equity ratio by one standard deviation rises banks' typical willingness to pay by 3.6 basis points.

Additionally, we find that persistent banks affect the shape of the aggregated bid curve in a plausible way. In fact, our results indicate that an increase of the fraction of persistent banks by ten percentage points reduces bid shading behavior by roughly 4.2 standard deviations. The same increase in the fraction of dependant banks increases the disproportional recourse to the primary money market by roughly 1.12 standard deviations. Both findings are revealing. First, banks who are "persistent" to the central bank's liquidity provision may be dependant upon this liquidity channel simply because they will find it more difficult to obtain funding from alternative sources. Second, banks that participate persistently in ECB's MROs may be considered as more "experienced" bidders who know the auction procedure well enough to place their bid-quantity schedules more successfully. Alternatively, the latter finding may indicate that dependant financial institutions have less incentives to perform bid shading as the MROs constitute their main funding source.

According to Hypothesis 4, an overall increase in banks' willingness to pay should follow large adverse price changes in the asset market during crises periods. Our estimate supports this theoretical mechanism. In fact, considering a rise in the log of Vstoxx by one standard deviation (equivalent to a 1.2 percentage point increase) will lead to a rise of $\hat{\tau}$ by 5.8 basis points. Additionally, we find that the stock market volatility influences $\hat{\alpha}$. This is intuitive as the number of alternative funding sources may diminish with increasing market illiquidity. Hence, banks want to make sure that they cover their liquidity needs and thus increase also their (excessive) demand in the primary money market. We find a change in the log of Vstoxx by one standard deviation to elevate $\hat{\alpha}$ by 0.22 standard deviations.

Furthermore, we find that the lower the average share of banks' ratio between tradable assets and their total assets the more aggressive will financial institutions place their bids in the MRO auctions. In fact, a one percentage point decrease of this measure will increase $\hat{\tau}$ by 3.1 basis points. This is in line with Hypothesis 5. In addition, we find that a relatively high level of maturity mismatch in the market has a significant and plausible impact on $\hat{\alpha}$ and $\hat{\tau}$. An increase of the average share by one percentage point increases $\hat{\alpha}$ and $\hat{\tau}$ by 0.39 standard deviations and 2.8 basis points, respectively.

Table 5: Determinants of Aggregate Liquidity Demand: Summary of Results

		Pre-Crisis			Crisis		
		$\hat{\alpha}$	$\hat{\lambda}$	$\hat{\tau}$	$\hat{\alpha}$	$\hat{\lambda}$	$\hat{\tau}$
Remaining Required Reserves	(std)	✓	✓	✓			✓
Equity Ratio	(std)					✓	✓
Persistent Banks	(%)				✓	✓	
Vstoxx	(log)				✓		✓
Maturity Mismatch	(%)	✓		✓	✓		✓
Tradable-to-Total-Assets	(%)	✓	✓				✓

Notes: '✓' denotes that our results presented in Table 3 are in line with our theoretical predictions summarized in Table 2.

2.5 Conclusion

Banking theory suggests a strong interplay between the way banks raise funding in money markets and the liquidity of broader financial markets. Our understanding of how the banking sector demands liquidity as a whole is, however, hampered by the absent comprehension of the key determinants of aggregate liquidity demand. The first contribution of this paper is to identify an aggregate liquidity demand function for the German banking sector. Our second contribution is to use this demand curve to gain a deeper insight into the demand pattern of the German banking sector before and during the recent crisis period. Our third contribution is to test the predictions of recent theories on the determinants of aggregate liquidity demand. This analysis strongly benefits from a rich and unique data set that we obtained from Deutsche Bundesbank.

Our findings show that the larger the need for liquidity reallocation through the secondary money market, the larger the premium that banks are willing to pay for funding in the euro area primary market for reserves. This might result from a fear that some banks obtain market power in the secondary money market and squeeze liquidity-short banks. Second, our results indicate that during times of low market liquidity more volatile asset prices increase the aggregate demand for central bank reserves. In that sense, we complement Nyborg and Östberg (2010). While they show that tensions in the interbank money market can feed into asset prices of the broader financial system, our paper provides strong evidence that high volatility of asset prices can affect banks' demand for liquidity. The strong evidence for both channels suggests that liquidity spirals (Brunnermeier, 2009) exist. Third, we find that a large dispersion of banks' equity ratios, as a measure of the heterogeneity of credit risk in the banking sector, induces both a more aggressive bidding strategy and a bid shading behavior. Fourth, our analysis reveals that an increase in the ratio of banks that persistently refinance through the primary money market during the financial crisis decreases bid rate dispersion. And fifth, a large stock of tradable assets that banks hold on the balance sheets is shown to reduce banks' refinancing needs through the primary money market. And sixth, our results suggest that a high level of maturity mismatch of the German banking sector increases banks' dependence on the primary money market. Thus in sum, our results show that tensions in financial markets and adverse shocks to the stability of the banking sector increase banks' demand for reserves.

Our results strongly support the ECB's decision to abandon its liquidity neutral allotment policy in October 2008. Ever since, the ECB regularly states that this change is only of temporary nature and will be reversed as soon as the strains are mitigated, see European Central Bank (2010). The findings of our analysis, however, challenge the resumption of the neutral liquidity provision policy for the post-crisis monetary policy practice. With such a policy, a central bank does not accommodate shocks to the aggregate reserve demand. Therefore, an increase in aggregate reserve demand resulting from detrimental shocks to the financial systems' stability leads to an increase in the equilibrium rate in the primary money market and supposedly also to higher rates in secondary money markets. This, in turn, may destabilize liquidity-short banks aggravating tensions in the financial system. For instance, if banks' liquidity demand increases in the primary market for reserves because asset markets happen to be illiquid, the equilibrium rate will increase. The resulting tensions in money markets impair the liquidity of financial markets further, raising the demand for central bank reserves. Consequently, a liquidity neutral allotment policy gives rise to self-enforcing liquidity crises. Keeping the aggregate supply of reserves over the reserve maintenance period at the level of the required holdings and only accommodating the banks' desire to front-load the fulfillment of reserve requirements, as the ECB did at the wake of the crisis, is according to our findings just not sufficient to break this vicious circle.

In order to avoid a contribution to adverse liquidity spirals, central banks should accommodate shocks to reserve demand by increasing the supply of reserves, in particular if these shocks result from instabilities in the banking sector or in the general financial system. However, to tackle a liquidity demand shock properly, central banks have to rely on valid estimates of its size. That is, central banks must be aware of the determinants of reserve demand and how changes of those determinants shape the level and slope of market liquidity demand. This is a particularly essential issue, since many of those determinants are themselves affected by tensions in the money market as our results indicate. Therefore, when deciding about the optimal allotment policy the central bank has to take into account the feedback that an accommodative allotment has on tensions in the banking system and ultimately on the demand for reserves.

2.6 Appendix to Chapter 1

2.6.1 Goodness of Fit

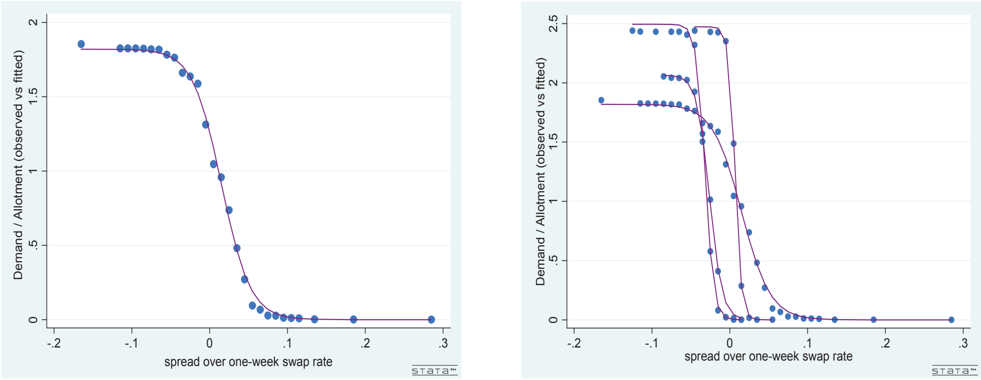
In order to assess the goodness of our model fit, we estimate the excessive liquidity demand per auction by using our parameter estimates ($\hat{\theta}_t = (\hat{\alpha}_t, \hat{\lambda}_t, \hat{\tau}_t)'$) and compare these estimates with the actual observed data. More precisely, we determine for each auction t the fitted quantities, $\hat{l}^d_{it} = f(\widetilde{r}_{it}; \hat{\theta}_t)$, at each ordered yield class $\widetilde{r}_i$, $\forall i = 1, \ldots, n$ and compare these fitted quantities with the observed values of l^d_{it}. Based on this comparison, Table 6 provides a cross-auction evaluation by the means of mean absolute deviation (MAD) and the median absolute deviation (MEAD). With a value of 0.059 and 0.040, respectively, our model can be considered to fit the observed data astonishing well. Figure 5 shows exemplarily the fit of our model graphically. It contrasts the observed aggregated bid curves from Figure 1 (dots) with the fitted values using our model with estimates parameters (solid line).

Table 6: Fitting Evaluation Statistics

Parameter estimates	mean	std	MAD	MEAD
l^d	1.59	1.23		
$\hat{l}^d$	1.60	1.20	0.06	0.04

Notes: This table provides a cross-auction summary of observed (l^d) and fitted ($\hat{l}^d$) quantities.

Figure 5: Graphical Illustration of the Goodness of Fit



(a) One aggregate bid curve (b) Four aggregate bid curves

Notes: The graphs show exemplarily the fitted values (solid line) and the observed quantities (dots) for the aggregate bid curves presented in Figure 1.

2.6.2 Alternative Illustration of the Goodness of Fit

In this section, we follow Boukai and Landsberger (1999) and compare the fitted and observed yields from a different perspective. Therefore, we consider two particular components of the MRO auction outcome, i.e. (i) the marginal or stop-out rate and the (ii) (quantity-)weighted average rate of all successful bids. The former represents the yield at which the last bidder is still satisfied, i.e. where the total amount to be allotted is exhausted. The latter reflects the quantity-weighted average of all *successful* bids per auction. Both interest rates are published by the ECB on behalf of the Eurosystem. To illustrate the goodness of our model fit, we calculate both the marginal rate and the weighted average rate for each auction using our fitted logistic curve.

To estimate the marginal rate, we use the fact that at this rate liquidity demand equals liquidity supply, such that:

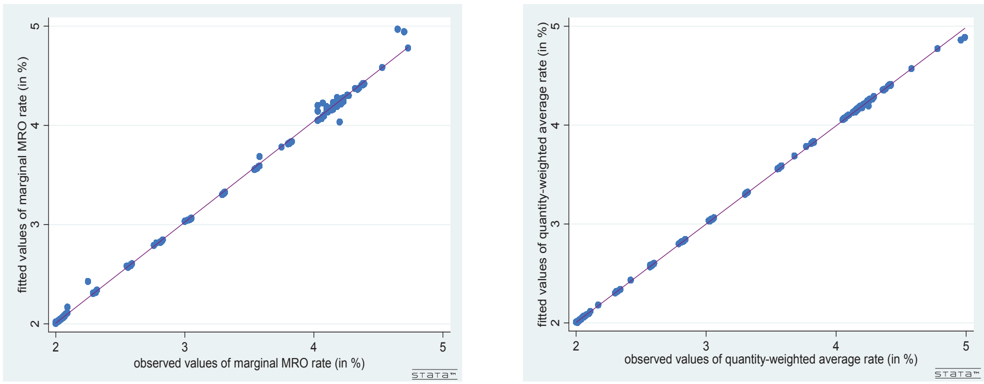
$$L_{it}^{d} = \frac{a_t}{1 + exp(\frac{(\tilde{r}_{it} - \tau_t)}{\lambda_t})} = \tilde{L}_t^s \tag{2.8}$$

Hence, rearranging Equation (2.8) allows us to predict the marginal rate by using our parameter estimates as follows:

$$r_t^{\hat{mr}} = \left(\hat{\tau}_t + \hat{\lambda}_t log(\hat{\alpha}_t - 1)\right) + swap1w_t \tag{2.9}$$

where $\hat{\alpha} = \frac{\hat{a}}{\bar{L}^s}$. We plot both the fitted marginal MRO rate and the fitted weighted average rates against their respective actual values announced by the ECB immediately after each auction, see Figure 6. In total, there are 240 pairs of fitted and observed values. As our data follows the 45 degree line, we conclude that our model yields an excellent fit of observed values.

Figure 6: Alternative Graphical Illustration of the Goodness of Fit



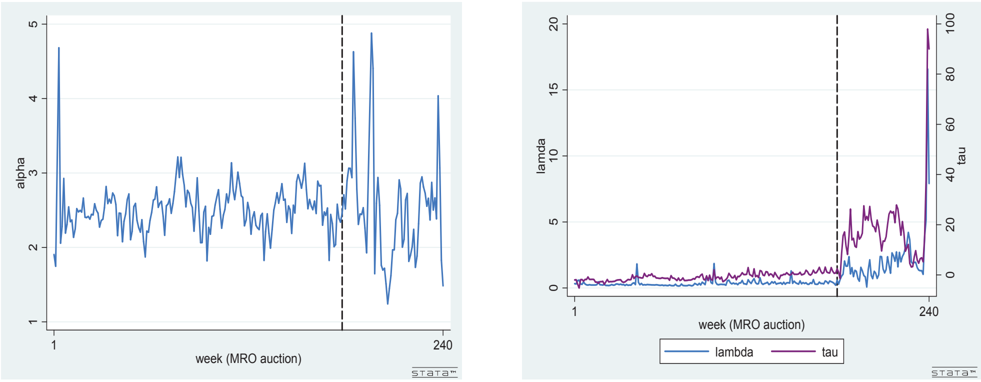
(a) Fitted vs observed marginal MRO rate

(b) Fitted vs observed weighted average rate

2.6.3 Alternative Specification: Results with Repo Rates

This section uses an alternative benchmark yield, i.e. the one-week repo rate, to make individual bids comparable across Eurosystem's MRO auctions. As in Equation (2.1), we substract the correspondingly dated one-week repo rate and re-estimate Equation (2.4). The summary statistics are presented in Table 7. Obviously, $\hat{\alpha}$ remains unaffected. For $\hat{\lambda}$ and $\hat{\tau}$ our results are slightly different, yet qualitatively similar to those presented in Table 1. While before the crisis bid shading is performed rather weakly, the dispersion of bids increase after August 2007. The estimates for τ indicate that before the onset of the crisis the one-week repo rate exceeded the typical willingness to pay on average across auctions. During the crisis, however, banks are willing to pay more than roughly 18 basis points above the respective repo rate. These results are qualitatively the same as presented in Table 1.

Figure 7: Estimation of Model Parameters with Alternative Specification



(a) Estimation of the excess liquidity demand (α)

(b) Estimation of the bid rate dispersion (λ) and the willingness to pay (τ)

Notes: These graphs show the estimations of the model parameter where the one-week repo rate was used to benchmark the reported bids For further details see Figure 4.

Table 7: Summary Statistics: Parameter Estimates (with Alternative Specification)

Parameter estimates	units	mean	std	min	max
09 Mar 2004 - 31 Jul 2007: 178 auctions					
$\hat{\alpha}$		2.49	0.27	1.75	3.21
$\hat{\lambda}$		0.34	0.20	0.14	1.85
$\hat{\tau}$	bp	-0.74	1.47	-5.19	3.14
08 Aug 2007 - 09 Oct 2008: 62 auctions					
$\hat{\alpha}$		2.51	0.75	1.24	4.88
$\hat{\lambda}$		2.18	2.42	0.07	16.58
$\hat{\tau}$	bp	18.13	15.99	-1.39	97.93

Notes: For further details, please refer to Table 1.

2.6.4 Marginal Demand and Elasticity along a Market Bid Function

This section shows the close relationship between the parameters of the logistic curve and the price elasticity of demand. For this purpose, we consider the general logistic representation:

$$f(\widetilde{r},\vartheta) = \frac{\alpha}{1+exp\big(\frac{\widetilde{r}-\tau}{\lambda}\big)}, \tag{2.10}$$

where ϑ is a vector of the parameters, i.e. $\vartheta = (\alpha,\lambda,\tau)'$. To show that this expression is continuously differentiable for any value of $\widetilde{r}$, we define:

$$f(\widetilde{r},\vartheta) = \frac{\alpha}{g(\widetilde{r},\vartheta)} \tag{2.11}$$

such that

$$f'(\widetilde{r},\vartheta) \equiv \frac{\partial f(\widetilde{r},\vartheta)}{\partial \widetilde{r}} = \frac{-\alpha g'(\cdot)}{g(\cdot)^2} \tag{2.12}$$

with $g(\cdot) = \big(1+exp\big(\frac{\widetilde{r}-\tau}{\lambda}\big)\big)$ and $g'(\cdot) = \frac{1}{\lambda}\big(exp\big(\frac{\widetilde{r}-\tau}{\lambda}\big)\big)$. Hence the derivative with respect to $\widetilde{r}$ becomes:

$$f'(\widetilde{r},\vartheta) = \frac{-\alpha\left(exp\big(\frac{\widetilde{r}-\tau}{\lambda}\big)\right)}{\lambda\left(1+exp\big(\frac{\widetilde{r}-\tau}{\lambda}\big)\right)^2} \tag{2.13}$$

The marginal normalized rate is therefore unimodal and the minimum is obtained at $\widetilde{r}=\tau$. At this point $f'(\tau,\vartheta) = \frac{\alpha}{4\lambda}$. The elasticity along the complete aggregate bid curve can then be computed as follows:

$$\varepsilon_d(\widetilde{r}) \equiv \frac{\partial log f(\cdot)}{\partial log \widetilde{r}} = \frac{\partial log f(\cdot)}{\partial \widetilde{r}} \cdot \left(\frac{\partial log \widetilde{r}}{\partial \widetilde{r}}\right)^{-1} \tag{2.14}$$

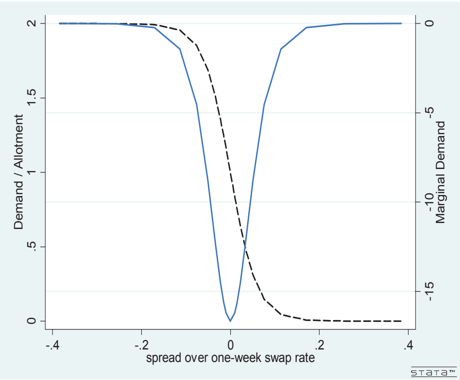
$$= \widetilde{r} \cdot \frac{\partial log f(\cdot)}{\partial \widetilde{r}} = \widetilde{r} \cdot \frac{\partial log f(\cdot)}{\partial f(\cdot)} \cdot \frac{\partial f(\cdot)}{\partial \widetilde{r}} \tag{2.15}$$

$$= \frac{\widetilde{r}}{f(\cdot)} \cdot \frac{\partial f(\cdot)}{\partial \widetilde{r}} \tag{2.16}$$

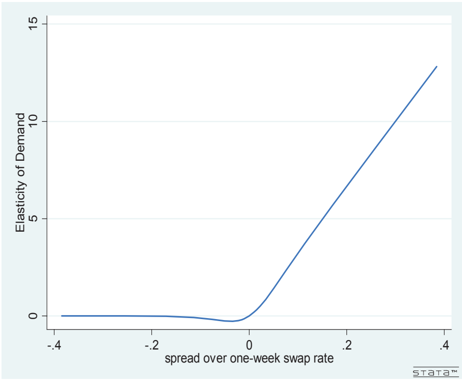
$$= \frac{\widetilde{r} \cdot exp\big(\frac{\widetilde{r}-\tau}{\lambda}\big)}{\lambda\left(1+exp\big(\frac{\widetilde{r}-\tau}{\lambda}\big)\right)} = \frac{\widetilde{r}}{\lambda\left(1+exp\big(\frac{\tau-\widetilde{r}}{\lambda}\big)\right)} \tag{2.17}$$

The elasticity achieves its minimum at $\widetilde{r}^* < \tau$. For any $\widetilde{r} < \widetilde{r}^*$ the elasticity corresponds to $\lim_{\widetilde{r}\to-\infty} \varepsilon_d(\widetilde{r}) = 0$ since $\lim_{\widetilde{r}\to-\infty} exp\big(\frac{\tau-\widetilde{r}}{\lambda}\big) = \infty$. For $\widetilde{r} > \widetilde{r}^*$, the elasticity increases linearly in $\widetilde{r}$ at the constant rate $\frac{1}{\lambda}$ because $\lim_{\widetilde{r}\to\infty} \varepsilon_d(\widetilde{r}) = \frac{\widetilde{r}}{\lambda}$ for $\lim_{\widetilde{r}\to\infty} exp\left(\frac{\tau-\widetilde{r}}{\lambda}\right) = 0$. At $\widetilde{r} = \tau$, the elasticity reaches $\varepsilon_d(\tau) = \frac{\tau}{2\lambda}$. Both marginal demand and the elasticity along the market bid curve are shown in Figure 8.

Figure 8: Marginal Demand and Elasticity along an Aggregated Bid Curve



(a) Marginal demand



(b) Price elasticity of demand

Notes: These graphs show the marginal demand (dashed line, left graph) and price elasticity (right graph) along an aggregate bid curve with $\alpha = 2$, $\lambda = 0.03$ and $\tau = 0$ using Equation (2.13) and (2.14), respectively.

2.6.5 Times Series Characteristics and Correlation

Table 8 also reports the time-series characteristics of our three parameter estimates. The augmented Dickey-Fuller test suggests a rejection of the null hypothesis that the parameters have a unit root, i.e. that they are $I(1)$. We test the robustness of these results by applying a KPSS test following Kwiatkowski et al. (1992), that tests whether a series is $I(0)$. Both test statistics confirm that our parameter estimates can be considered as stationary variables.

Table 8: Unit Root Tests

	ADF	KPSS	ADF	KPSS
Parameter	09 Mar 2004 - 31 Jul 2007		08 Aug 2007 - 09 Oct 2008	
estimates	178 auctions		62 auctions	
$\hat{\alpha}$	-10.28*	0.08	-4.30*	0.12
$\hat{\lambda}$	-18.94*	0.13	-3.62*	0.08
$\hat{\tau}$	-4.71*	0.05	-3.29*	0.16

Notes: We provide the t-statistic and the LM-statistic for the Augmented Dickey-Fuller (ADF) test and the KPSS-test, respectively. The lag length for the ADF-test (with an intercept) is chosen according to the Schwarz Information Criterion while the bandwidth choice for the KPSS-test follows the Newey-West criterion using a Bartlett kernel. * indicate significance at the 5% level.

Table 9 presents the results from a Pearson covariance analysis. For both the pre-crisis and crisis period, the correlation coefficients $\rho_{\hat{\alpha},\hat{\tau}}$ and $\rho_{\hat{\alpha},\hat{\lambda}}$ are both negative, whereas $\hat{\tau}$ and $\hat{\lambda}$ appear to be positively correlated. These results reflect the stability of the generating process of market demand. For instance, $\rho_{\hat{\tau},\hat{\lambda}}$ shows that banks' aggressive bidding (large values of $\hat{\tau}$) is associated with higher bid shading behavior, i.e. higher $\hat{\lambda}$ and thus decreasing price elasticity of reserve demand. Since aggressive bidding strategy ensures some liquidity allocation, this finding illustrates how German financial institutions protect themselves while bidding aggressively. Not surprisingly, we find this correlation to be higher during the crisis.

Table 9: Correlation Analysis Among Estimated Parameters

	09 Mar 2004 - 31 Jul 2007	08 Aug 2007 - 09 Oct 2008
$\rho_{\hat{\alpha},\hat{\tau}}$	-0.41 [0.0000]	-0.23 [0.0846]
$\rho_{\hat{\alpha},\hat{\lambda}}$	-0.35 [0.0000]	-0.46 [0.0003]
$\rho_{\hat{\lambda},\hat{\tau}}$	0.47 [0.0000]	0.71 [0.0000]

Notes: p-values are presented in parentheses.

2.6.6 Structural Break Test

This section uses structural break tests to investigate whether the financial crisis had a significant impact on the relationship between the determinants of the aggregated bid curve and its parameters $\hat{\alpha}$, $\hat{\lambda}$, and $\hat{\tau}$. To that aim, the Quandt-Andrews test for unknown breakpoints is applied to our Equation (2.7):

$$\begin{aligned} \hat{\theta}_t &= c + \alpha_1 D_t^{lw}\text{Res}_t + \alpha_2(1 - D_t^{lw})\text{Res}_t + \alpha_3 EQR_t + \alpha_4 PB_t \\ &+ \alpha_5 Vstoxx_t + \alpha_6 MatMis_t + \alpha_7 TA_t + \beta' X_t + \upsilon_t \end{aligned} \quad (2.18)$$

We test whether there has been a break in all the equation parameters for the full sample from April 09, 2004 to October 09, 2008. The Quandt-Andrews test is based on standard F-statistics, see Andrews (1993). $Max\ F$ denotes the maximum of the individual *F*-statistics while the *Ave* statistic refers to their average. Since the break point is unknown, the asymptotic distribution of both test statistics are non standard and depend on the number of coefficients that are allowed to break and on the fraction of the sample that is examined. Note that the distributions become degenerate as the first period tested approaches the beginning of the equation sample, or the end period approaches the end of the equation sample. To compensate for this behavior it is generally suggested to exclude the end of the equation sample from the testing procedure. Following Andrews (1993), we apply a symmetric "trimming" of 10%. Approximate asymptotic *p*-values are calculated in line with Hansen (1997). The results show that the determinants of the aggregate bid curve have significantly changed since the start of the financial crisis.

Table 10: Quandt-Andrews Unknown Breakpoint Test

Statistic	Date	Max F	Ave F
$\hat{\alpha}$	Oct 17 2007	31.92 [0.0034]	21.21 [0.0002]
$\hat{\lambda}$	Aug 22 2007	56.41 [0.0000]	18.95 [0.0005]
$\hat{\tau}$	Aug 08 2007	93.82 [0.0000]	17.92 [0.0020]

Notes: Estimated break date and approximate asymptotic p-values in line with Hansen (1997) in parenthesis. Test sample: April 09, 2004 to October 09, 2008 for weekly parameter estimates $\hat{\theta}_t = (\hat{\alpha}_t, \hat{\lambda}_t, \hat{\tau}_t)'$. Number of breaks compared: 177.

For $\hat{\tau}$, the test statistics choose the first MRO auction after the outbreak of the crisis as the main candidate for a significant break point. For $\hat{\lambda}$ and $\hat{\alpha}$, the statistics point to a breakpoint at August 22 and October 17 2007, respectively. These results imply that the determinants of these two parameter estimates have also undergone a structural change during the second half of 2007.

Table 11: Chow's Breakpoint Test

$\mathcal{H}_0$: No (structural) breaks at specified breakpoints			
	Test Date	F-statistic likelihood ratio	Log
$\hat{\alpha}$	Aug 08 2007	2.54^{**}	21.65^{***}
$\hat{\lambda}$	Aug 08 2007	3.55^{***}	29.66^{***}

Notes: ***,**,* indicates significance at the 1%, 5%, 10% level. The F-statistic is based on the comparison of the restricted and unrestricted sum of squared residuals. The log likelihood ratio statistic compares the restricted and unrestricted maximum of the (Gaussian) log likelihood function.

However, Table 11 shows the results of a Chow's breakpoint test at a specified date. The idea of this test is to fit the Equation (2.18) separately for each given subsample and check whether there are significant differences in the estimated equations. These differences are interpreted as structural change in the relationship. The reported *F*-statistic is based on the comparison of the restricted and unrestricted sum of squared residuals. The *log likelihood ratio* statistic is refers to the comparison of the restricted and unrestricted maximum of the (Gaussian) log likelihood function. While the former has an exact finite sample *F*-distribution, the *LR* test statistic has an asymptotic χ^2 distribution with k degrees of freedom, where k is the number of parameters in the equation. Both statistics reveal also a structural change for the determinants of $\hat{\alpha}$ and $\hat{\lambda}$ as of August 8, 2007.

Chapter 3

Monetary Transmission Right from the Start: The Response of the Money Market to the ECB's Main Refinancing Rates

"In our time, the curse is monetary illiteracy, just as inability to read plain print was the curse of earlier centuries"
(Ezra Pound, 1938)

3.1 Introduction

Weekly main refinancing operations (MROs) are of overwhelming importance for the monetary policy implementation of the European Central Bank (ECB). The liquidity supply in MROs should ensure that short-term money market rates closely follow the MRO rates and that their volatility remains well contained, see e. g. Cassola and Morana (2008) and Ejerskov et al. (2008). This central aim of monetary policy implementation has never been an easy task. Even before the financial crisis, a puzzling and unintended upward trend in the spread between the European overnight rate (Eonia) and MRO rates indicated that the monetary transmission mechanism is not sufficiently understood, see Linzert and Schmidt (2011).[33] Since the start of the financial crisis, the spreads between the ECB's main refinancing rates and money market rates have been huge and persistent. In order to shed more light on the starting point of the monetary transmission process in the euro area, this paper investigates how the European money market responds to MRO auction outcomes.

On the allotment day, the ECB publishes the number of bidders, total allotment and total bids together with the marginal and the weighted average allotment rate of the MRO. All these variables may contain new information about the expected course of monetary policy and the situation in the money market. This paper assesses the role of MROs for the monetary transmission mechanism by estimating the response of money market rates to the various aspects of an MRO auction outcome.

Our study can be related to two groups of papers. First, there is a growing empirical literature on the dynamics and the volatility of overnight rates. Recent examples include Bartolini and Prati (2006), Pérez Quirós and Rodríguez Mendizábal (2006), Colarossi and Zaghini (2009), and Nautz and Scheithauer (2009). All these contributions investigate how distinguishing features of the central bank's operational framework influence the behavior of overnight rates. Other than this paper, the do not focus on the response of the overnight rate to auction outcomes. The second group of papers explores banks' bidding behavior in central bank auctions, see e. g. Bindseil et al. (2007), Bindseil et al. (2009), and Cassola et al. (2009). Using individual bidding data, it can be shown that money market conditions significantly affect banks' bidding behavior. These papers try to explain the auction outcome but do not consider its repercussions on the money market.

The current paper fills this gap and explores the impact of the ECB's MRO auctions on short-term money market rates in the euro area using both daily and

[33] In contrast to earlier estimates of the liquidity effect, even the ECB's provision of excess liquidity in MROs could not bring the Eonia back to its intended level, see European Central Bank (2006). In the U. S. , the empirical relevance of the liquidity effect has been analyzed e. g. by Carpenter and Demiralp (2008) and Thornton (2008).

intra-day data of overnight rates. Longer-term Eonia swap rates are employed to examine how the auctions affect the market's expectations about future Eonia movements. Our results show that the recent crisis significantly impeded the first step of the monetary transmission mechanism. Before the financial crisis, MRO auction outcomes helped to stabilize the money market. If e. g. the spread between the Eonia and the new MRO rate was above average, the Eonia would adjust accordingly. Since the outbreak of the crisis, however, the stabilizing effect of MRO auctions on the Eonia level has disappeared. In contrast, MRO auction outcomes distorted by safety bids exacerbated the disconnection of money market rates from the policy-intended interest rate level. Therefore, our results provide strong support for the ECB's decision to re-stabilize banks' refinancing conditions by introducing a fixed rate full allotment policy for the whole maturity spectrum of its refinancing operations as of October 2008.

The remainder of the paper is structured as follows. In Section 3.2, we briefly review the role of MRO auctions in the operational framework of the ECB and consider the timing of the auctions. Section 3.3 introduces the auction variables and discusses their expected influence on the money market. Section 3.4 presents the empirical results on the impact of MRO auction outcomes on money market rates before and during the crisis. Section 3.5 summarizes our main results and offers some concluding remarks on the choice of MRO auction formats for the post-crisis period.

3.2 The Role of MRO Auctions in the ECB's Operational Framework

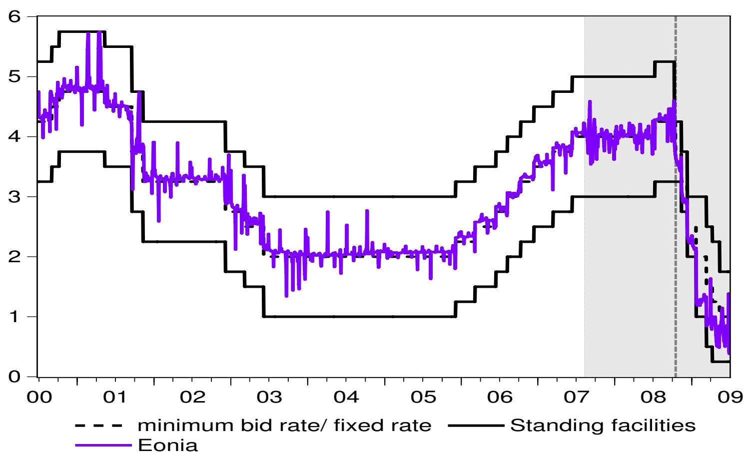
3.2.1 Monetary Policy Implementation

The ECB implements its monetary policy through a framework in which the banking sector operates in a liquidity deficit vis-á-vis the Eurosystem. The weekly main refinancing operations (MROs) cover the bulk of banks' liquidity demand and play the pivotal role in signalling the monetary policy stance. From June

2000 until October 2008, MROs were conducted as variable rate tenders, i. e. as price-discriminatory multi-unit auctions where banks are allowed to submit multiple price-quantity bids. In variable rate tenders, the resulting repo rates partially depend on the bids of banks and, thus, are not fully under the ECB's control. Therefore, the ECB pre-announces a minimum bid rate. The interest rates actually applied in the MROs can be viewed as the first step in the transmission of monetary policy and should determine the level of short-term interest rates in the euro area's money market.

Unlike the U. S. Federal Reserve Bank, the ECB has never announced an explicit operational target for its monetary policy implementation, see e. g. Ho (2008). However, there is no doubt that the ECB's liquidity policy aims at stabilizing the shortest money market rate, Eonia, to a level close to its main refinancing rates, see e. g. Cassola and Morana (2008) and Ejerskov et al. (2008). Figure 9 shows the corridor in which the Eonia fluctuates between the two standing facilities and the minimum bid rate as its mid-point.

Figure 9: Interest Rate Corridor of the ECB



Notes: The light shaded area refers to the crisis period as of August 9, 2007. The dashed vertical line represents the ECB's adoption of the fixed rate tender procedure with full allotment as of October 15, 2008.

On August 9, 2007, tensions surrounding assets backed by US subprime mortgages started to spill over to money markets around the world, leading to liquidity shortages in these markets. In the euro area, the overnight rate rose substantially following an increased liquidity demand in the overnight market. As a consequence, the ECB adjusted the liquidity provision pattern in its weekly MROs significantly. In order to account for the changes in the demand and supply of liquidity in the ECB's MROs, we allow money markets to respond differently to auction results after August 2007. We explore the link between the Eonia and MROs for the crisis and pre-crisis sample separately. In fact, splitting our sample on August 9, 2007 is also implied by structural breakpoint tests, see Section 3.6.1 in the Appendix.

After Lehman Brothers filed for bankruptcy on September 15, 2008, the crisis intensified. Banks became even more reluctant to engage in interbank money market trading and relied to an increasing extent on the ECB's refinancing operations, see e. g. Hauck and Neyer (2010). On October 15, 2008, the ECB responded to the exacerbated crisis and switched from the variable rate tender format to a fixed rate full allotment policy, hence satisfying the full liquidity demand of the banking sector.[34] The information content of an auction outcome is very limited under this format: In a fixed rate tender, the repo rate is pre-announced and all MRO rates are equal by construction. Moreover, due to full allotment, the cover-to-bid ratio is always one. Therefore, in the following empirical analysis on the information content of MROs, we shall focus on the variable rate tender period. Yet, our results may shed light on the rationale behind the ECB's switch to the fixed rate full allotment tender format.

3.2.2 Overnight Rate Dynamics, MRO results, and the Martingale Hypothesis

The Eurosystem applies a framework in which banks' demand for liquidity is created and governed by reserve requirements. This implies that euro area financial institutions are obliged to hold a minimum amount of reserves with the Eurosys-

[34] On August 4, 2011, the Eurosystem decided to continue conducting its MROs as fixed rate tender procedures with full allotment for as long as necessary, and at least until the end of the last maintenance period of 2011 on 17 January 2012, see Eurosystem's press release webpage. For further explanations, refer to European Central Bank (2010).

tem. For the fulfilment of these required reserves, banks are granted an averaging scheme. That is, compliance with the reserve requirement is judged by banks' average end-of-day reserve balances over a reserve maintenance period. Due to the averaging provision, the reserve holdings on any day of a given maintenance period may be considered as perfect substitutes for purposes of satisfying reserve requirements on any other day within the same maintenance period. Hence, the overnight rate on Monday ($i_{b,t}$), the day before auction t, should be equal to the interest rate that banks' funds traders expect to hold on Tuesday, $i_{b,t} = E_{b,t}(i_{a,t})$, where $E_{b,t}(i_{a,t})$ denotes the expectation formed on the basis of information available on Monday as to the value of Tuesday $i_{a,t}$. The reason for this property is that any misalignment between the current overnight rate and its expected future value within the maintenance period would trigger attempts on the part of the banks to reschedule their fulfilment of reserve requirements for the remainder of the maintenance period. This in turn would ultimately lead to an equalization of interest rates, see Hamilton (1996), Bindseil et al. (2003) and Bindseil (2004a).

From an ex ante view, interest rates should therefore be constant within a maintenance period, i.e. the expected future overnight rates within a maintenance period should never diverge from one day to the next. The logical implication of this argument is that interest rates should follow a martingale within the maintenance period. For the euro area, Würtz (2003) and Moschitz (2004), for instance, provide empirical evidence supporting the martingale hypothesis. Deviations from the martingale property are found to be characteristics of the end-of-calendar and end-of-maintenance-period effect and thus considered as naturally harmless, see e.g. Hamilton (1996), Bindseil et al. (2003).

But, in practice, when uncertainty prevails with respect to the factors determining the overnight rate, news will constantly emerge in the course of the maintenance period, and thus the overnight rate will normally not be constant from an ex post perspective. Within a reserve maintenance period, however, money market rates should only adjust to new information and, in particular, to the unexpected components of an auction outcome. It is noted that a potential response of money market rates to the MRO auction outcome should not be seen as a violation of the martingale hypothesis but, rather, as a result of the fact that any piece of new information affecting the money market rates will be fully reflected in the same day's interest rates. This line of argument is also consistent with the weak form of the efficient market hypothesis according to which economic agents cannot devise an investment strategy based on the history of past (price) patterns, see Fama (1984). In that sense, if money market rates respond to auction outcomes, it is because of an adjustment process triggered by new information revealed to economic agents.

3.2.3 Measuring the Money Market Response to an MRO Auction Outcome

In the MROs of the ECB during our sample, banks are invited to submit their bids from Monday 3:30 p. m. CET to Tuesday 9:30 a. m. CET. On Tuesday 11:20 a. m. CET, the ECB communicates the auction outcome via its wire service. The response of the money market to an auction outcome should be reflected in overnight rates observed immediately after the auction results are available. Let i_b and i_a be the market rates valid *b*efore and *a*fter banks are informed about the auction outcomes. The money market response to the auction is then revealed in $\Delta i = i_a - i_b$. We measure Δi in three ways and thereby cover three main trading segments of the money market. First, in line with the empirical literature, we use daily data of the Eonia, the European Over-Night Index Average published by the ECB.[35] Eonia rates refer to transactions carried out before the closing of real time gross settlement (RTGS) system at 6.00 p. m. CET and are published on the same evening. Since the bulk of money market transactions are carried out after the auction result is announced, the timing of MROs suggests to use Eonia rates of Monday (i_b) and Tuesday (i_a) to measure the money market reaction to an auction outcome.

If money markets react quickly to new information about the liquidity situation, the *average* overnight rate at the auction day might be only a poor approximation

[35] The Eonia is based on a panel of roughly 50 banks with the highest business volume in the euro area money market, see www.euribor.org. Following European Central Bank (2007a), the unsecured market remains mainly an overnight market segment, with roughly 70% of the volumes both in the lending and borrowing activities in the shortest maturity bucket.

for i_a and similar problems may apply to i_b. Therefore, in a second specification of Δi, we use intra-day broker quotes collected from Reuters at 9:30 a. m. CET and 11:25 a. m. CET for i_b and i_a, respectively. These rates are very close to the end of bid submission and the announcement of the auction outcome. Yet the available intra-day data has two shortcomings. Firstly, intra-day data cover only that part of the 'over the counter' (OTC) market trading that is processed through voice brokers.[36] Thus, transactions between banks directly are missing. And secondly, in contrast to the daily Eonia data, intra-day data only refer to unbinding quotes rather than actual transactions.

A third approximation of Δi uses daily data of Eonia swap rates with one-week maturity obtained from Reuters. The Eonia swap market, in general, serves as the main instrument to manage short-term interest risk exposures and covers roughly 40% of the overall OTC derivatives market, see e. g. European Central Bank (2007a). The one-week swap rate corresponds to the maturity of the MROs and measures the expected average Eonia over the next week. Thus, it is less affected by outliers than the daily Eonia. Because MROs are conducted only once a week, the one-week Eonia swap rate cannot be affected by expectations about future auction outcomes at an auction day. Since March 2008, the announcement of Eonia swap rates has changed from 4:30 p. m. CET to 11 a. m. CET. In line with the timing of MROs, the definition of Δi is adjusted accordingly.

Starting with the first price-discriminatory multi-unit auction on June 27, 2000, we collected 434 auctions until October 14, 2008. Intra-day data is only available from December 4, 2000 to June 17, 2008. For the sake of comparability, we will run all our regressions from December 4, 2000, to June 17, 2008. At the end of the reserve maintenance period, when no further MRO will be conducted, liquidity shortages or excess reserves can lead to dramatic increases of overnight rate volatility. It is well understood by the market that these seasonal interest

[36]According to European Central Bank (2007a), more than 90% of all interbank transactions in the OTC derivatives market (other than foreign exchange swaps) are traded directly or through voice brokers. Since data on bilateral trading is notoriously hard to obtain, we use transactions through voice brokers that account for 27% of the total turnover in OTC derivatives.

rate fluctuations are temporary and unrelated to monetary policy signals, see e. g. Nautz and Offermanns (2008). To ensure that our results are not driven by the large Eonia movements at the very last day of the reserve period, we excluded the auctions performed at those particular days from our regressions.[37] After these sample adjustments, we are left with 282 and 33 auctions before and during the crisis, respectively.

3.3 The MRO Auction Outcomes: Variables and Predictions

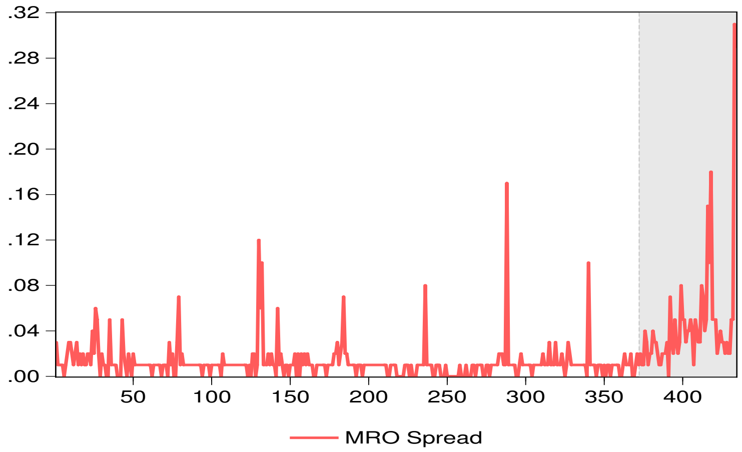
On the allotment day, the ECB publishes (i) the marginal rate (r_m) of the MRO, (ii) the quantity weighted average rate (r_w) of all successful bids, (iii) total bids and total allotments, and (iv) the number of bidders. All these variables may contain new information about the situation in the money market and the policy-intended interest rate level.

The ***marginal rate*** or stop-out rate of an MRO, r_m, depends on banks' bidding behavior and on the ECB's allotment decision. The martingale hypothesis suggests that deviations of the marginal rate from the overnight rate valid immediately before the auction, $r_m - i_b$ should affect banks' expectations about the future overnight rate. This in turn should imply that the overnight rate i_a adjusts accordingly. In an error-correction type adjustment equation of Δi, the coefficient of $r_m - i_b$ is expected to be positive.

Before the crisis, the ***weighted average rate*** of an MRO, r_w, used to be only a few basis points above the marginal rate. By contrast, after August 2007, the MRO spread, $r_w - r_m$, increased up to 30 basis points, see Figure 10. The MRO spread can be large for two reasons. On the one hand, it may indicate that the bulk of bids was submitted at relatively high rates because the demand for liquidity was stronger than expected. Particularly in the recent financial crisis, banks faced

[37]For the sake of robustness, two further observations were identified as outliers: the MRO with anomalous allotment one week after the terrorist attack on September 11, 2001, and the MRO distorted by the announcement of the six-month supplementary operation in April 2008.

Figure 10: Spread Between MRO Rates (in percent)

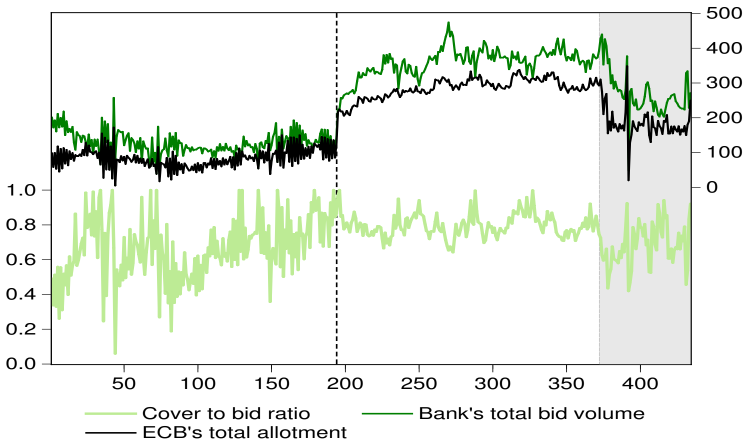


Notes: The MRO spread is defined as the difference between the weighted average and marginal MRO rate. Since the daily dataset has been reduced to the auction relevant days, the drawn data has *not* a daily frequency. The x-axis, therefore, refers to respective auction t. The light shaded area refers to the crisis period as of August 9, 2007.

great uncertainty regarding their future liquidity situation. According to Cassola et al. (2009), banks submitted more aggressive bids in order to make sure that they receive at least a minimum level of liquidity. On the other hand, large MRO spreads may reveal bidders' uncertainty about the auction's marginal rate, see e. g. Välimäki (2008). The increased heterogeneity of values for liquidity revealed by the auction and the failure of the interbank market to lead to an efficient allocation of liquidity among banks in the course of the crisis made it very difficult to forecast the marginal rate of MRO auctions. For both reasons, an MRO auction revealing a large MRO spread should lead to an upward pressure on the overnight rate.

The ***cover-to-bid ratio***, CBR, of an MRO is defined as the ratio between the ECB's total allotment and the banks' total bid volume, compare Figure 11. Large cover-to-bid ratios indicate that banks received a lot of refinancing relative to their bids. One might expect that overnight rates should always decrease with increasing cover-to-bid ratios. However, as Bindseil et al. (2007) already emphasized, a low cover-to-bid ratio only leads to money market tensions if it resulted from banks' misperceptions of the marginal rate and the situation in the money market. If banks bid seriously and the marginal rate of the MRO simply exceeded banks' willingness to pay, a low cover-to-bid ratio will not necessarily lead to increasing overnight rates. Until March 2004, banks anticipated future rate cuts of the ECB

Figure 11: MROs' Cover-to-Bid Ratio



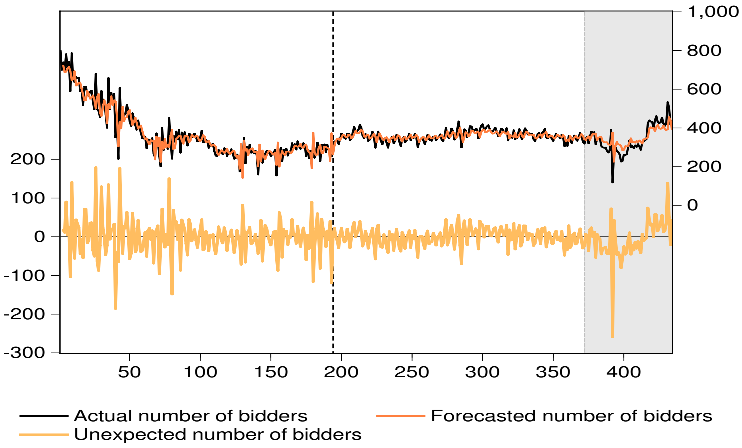
Notes: The aggregate bid volume and total allotment are in EUR billions. The black dashed line represents the introduction of the new operational framework as of March 2004. For further explanations, see Figure 10.

on several occasions and, therefore, simply refrained from bidding. As a result, banks' total bid volume was so low that the ECB could not allot the intended volume of reserves. Due to banks' underbidding, the cover-to-bid ratio peaked to one but due to the lack of reserves overnight rates increased sharply at the auction day. In order to stop the disturbing strategic bidding behavior of banks, the ECB adjusted its operational framework in March 2004. Reducing the MRO maturity from two to one week and synchronizing the interest rate decisions with the reserve requirement periods ensured that auction results are not affected by banks' expectations about future policy rates, see e. g. European Central Bank (2003). To avoid that our results are driven by underbidding episodes, we exclude these observations from the following regressions and allow for a different information content of cover-to-bid ratios before and after March 2004.[38]

The ***number of bidders*** in MROs has significantly declined since June 2000, see Figure 12. Following Bindseil et al. (2009), we estimated the new information

[38] The underbidding events refer to the MROs on 13 Feb, 10 Apr, 9 Oct and 6 Nov 2001, 3 Dec and 17 Dec 2002, 3 Mar, 3 Jun and 25 Nov 2003 and 20 Feb , see Bindseil (2004b).

Figure 12: Number of Bidders in MROs

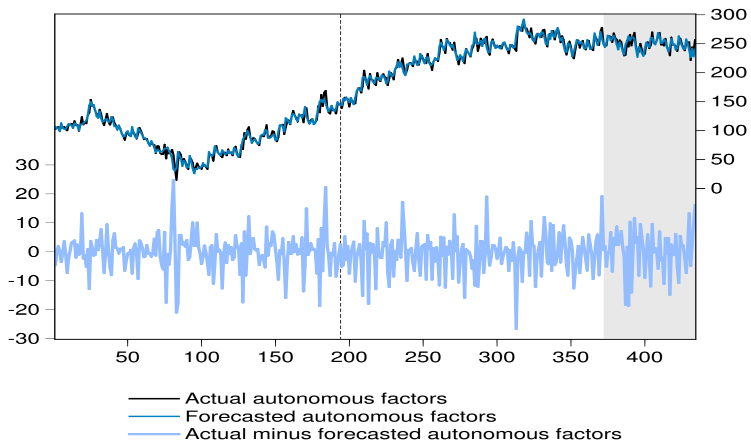


Notes: For further explanations, see Figures 10 and 11.

contained in the number of bidders, i. e. the unexpected part in this variable, employing a univariate forecast equation, see Section 3.6.2 in the Appendix. Note that alternative forecast and detrending methods would not affect our results in a significant way. In case of a surprisingly large number of bidders which should reveal an unexpectedly high demand for refinancing, the overnight rate should increase.

Daily autonomous liquidity factors and reserve requirements drive banks' liquidity needs. Since June 2000, the ECB uses weekly autonomous factors forecasts to rationalize its current allotment decision and to determine its benchmark allotment. If actual autonomous factors are higher than the ECB's benchmark allotment calculation would suggest, the liquidity situation should be tight leading to tensions in the overnight rate, see Linzert and Schmidt (2011). Therefore, the difference between ***updated forecasts and forecasted autonomous factors***, ΔAF, should be included as a control variable in the empirical analysis of the link between MROs and the money market. While the ECB's forecast of autonomous factors is known to the banks before the MRO auction is conducted, the updated values are provided on the allotment day together with the MRO auction results, between 11:15 a. m. CET and 11:20 a. m. CET. Therefore, we would expect ΔAF to increase daily overnight rates.

Figure 13: Updated Forecasts minus Forecasted Autonomous Factors around MROs (in EUR billions)



Notes: For further explanations, see Figures 10 and 11.

3.4 The Response of Money Market Rates to MRO Auction Outcomes

Our empirical results on the relationship between the ECB's MRO auctions and the money market are based on the following error-correction type adjustment equation for the money market rate,

$$\begin{aligned} \Delta i_t &= c + \alpha(r_m - i_b)_t + \beta(r_w - r_m)_t \\ &+ \gamma_C CBR_t + \gamma_B B_t + \gamma_A \Delta AF_t + \varepsilon_t, \end{aligned} \tag{3.1}$$

where for each auction t, $\Delta i_t = i_{a,t} - i_{b,t}$ denotes the change of the money market rate immediately after the MRO auction results have been published. α and β determine the impact of the marginal (r_m) and the weighted average MRO rate (r_w) on the Eonia. Since $r_w - r_m = (r_w - i_b) - (r_m - i_b)$, equation (3.1) is a re-parametrization of the adjustment equation which includes both equilibrium relationships between the auction and the money market rate, i. e. $(r_m - i_b)$ and $(r_w - i_b)$. Therefore, $\alpha = 0$ implies that the Eonia is disconnected from *both* MRO rates, since there is neither an equilibrium relation with the marginal nor with the weighted average MRO rate. In particular, in case of $\alpha = 0$ and $\beta \neq 0$, increased MRO spreads, $r_w - r_m$, may even exacerbate the disconnection of money market rates from the policy-intended interest rate level. In case of $\alpha \neq 0$ and $\beta = 0$, there is an equilibrium relation between the levels of the Eonia and the marginal rate while the weighted average rate plays no additional role. $\alpha = \beta \neq 0$ implies that $\alpha(r_m - i_b) + \alpha(r_w - r_m) = \alpha(r_w - i_b)$. In this case, the overnight rate is predominantly affected by the weighted average MRO rate. CBR and B denote the auction's cover to bid ratio and the unexpected part in the number of bidders, ΔAF controls for news concerning autonomous factors. According to Section 3.3, the expected signs of the coefficients are $\gamma_C < 0, \gamma_B > 0, \gamma_A > 0$.

3.4.1 The Connection between the Eonia and the MRO rates before the Financial Crisis

Table 12 shows the results obtained for the change of Eonia in response to an MRO auction outcome. In the pre-crisis sample, the estimates indicate a significant and plausibly signed response of the overnight rate to the newly announced main refinancing rates. Irrespective of the interest rate measure, $\widehat{\alpha} > 0$ implies an error-correction type level relationship between the Eonia and MRO rates. Specifically, for the daily and intra-day Eonia data, Wald tests cannot reject the null-hypothesis that $\alpha = \beta$. This suggests that the weighted average MRO rate, not the marginal rate, governs the level of the overnight rate. For the one-week Eonia swap rates, the relevant information revealed by MRO rates is contained in the marginal rate. In fact, the corresponding adjustment coefficient $\widehat{\alpha} = 0.8586$ is very close to one. Thus, news about the marginal MRO rate strongly influence market's expectations about the Eonia of the following week. In line with the central role of MROs in the transmission process of monetary policy, the evidence in favor of an error-correction type adjustment of the Eonia confirms that MRO auctions stabilized the Eonia before the crisis.

The results obtained for the impact of the cover-to-bid ratio CBR are also in line with expectations. Before the introduction of the new operational framework in 2004, results concerning the significance and sign of the estimated CBR coefficients are mixed which reflects the distortions in the CBR implied by banks'

Table 12: Money Market Response to an MRO Outcome

Money Market Response (Δi_t)

$$\Delta i_t = c + \alpha(r_m - i_b)_t + \beta(r_w - r_m)_t + \gamma_C CBR_t + \gamma_B B_t + \gamma_A \Delta AF_t + \epsilon_t$$

Auction Variables	Pre–Crisis: June 2000 - August 2007 Daily Eonia	Pre–Crisis: Intra Day Data	Pre–Crisis: 1–Week Eonia Swap Rates	Crisis: August 2007 - June 2008 Daily Eonia	Crisis: Intra Day Data	Crisis: 1–Week Eonia Swap Rates
$(r_m - i_b)$	0.5190***	0.2655***	0.8587***	−0.0725	0.0583	−0.0050
	[0.1301]	[0.0921]	[0.1209]	[0.0687]	[0.0674]	[0.0795]
$(r_w - r_m)$	0.5166**	0.2953*	0.1467	1.4565*	1.9740***	0.7891*
	[0.2354]	[0.1539]	[0.2295]	[0.8733]	[0.7260]	[0.4014]
Cover-to-Bid Ratio (CBR) before March 2004	0.0922***	−0.0287**	−0.0036			
	[0.0318]	[0.0119]	[0.0221]			
after March 2004	−0.0649**	−0.0541**	−0.0287	−0.2359*	−0.2523*	−0.2395***
	[0.0295]	[0.0223]	[0.0285]	[0.1227]	[0.1379]	[0.0600]
Number of Bidders (B)	0.0003*	0.0001	0.0000	0.0012***	0.0005	0.0034*
	[0.0002]	[0.0001]	[0.0010]	[0.0003]	[0.0003]	[0.0017]
Autonomous Factors (ΔAF)	0.0009**	0.0002	−0.0006***	0.0015*	0.0001	−0.0002
	[0.0004]	[0.0003]	[0.0002]	[0.0009]	[0.0012]	[0.0007]
Obs.	282	282	282	33	33	33
R^2	0.58	0.45	0.65	0.72	0.41	0.40

Wald tests of parameter equality: $H_0 : \alpha = \beta$ vs $H_1 : \alpha \neq \beta$

p-value	0.98	0.82	0.00	0.08	0.01	0.05

Notes: ***,**,* indicate significance at the 1%, 5%, 10% level. Newey-West HAC standard errors in parentheses. The index t denotes the number of the MROs covering the period December 2000 to June 2008.

strategic bidding behavior. After March 2004, the ECB's reform apparently re-established the information content of CBRs about banks' liquidity situation. According to our estimates, an increase of the cover-to-bid ratio by ten percentage points decreases the Eonia by about 0.5 basis points.

Further plausible, yet less significant results are obtained for the number of bidders. For daily data, we estimate that an unexpected increase of the number of bidders by 100 would decrease the Eonia by about 3 basis points. The results obtained for ΔAF, the variable reflecting news about autonomous factors, are more puzzling.

Although the ECB has always been eager to estimate and publish its forecasts on autonomous factors on a regular basis, the evidence on the information content of this variable for the money market is economically not significant.

3.4.2 The Disconnection between the Eonia and the MRO Rates during the Financial Crisis

For the crisis period, the results for the empirical relationship between the Eonia and the MRO rates are shown in the right panel of Table 12. They differ from those obtained for the pre-crisis period in two important aspects. First, the estimates imply that the Eonia and the effective key interest rates of the ECB have been disconnected. There is no significant error-correction type adjustment of the Eonia to the level of the MRO rates in the crisis period, i. e. $\alpha = 0$. As a consequence, MRO rates failed to stabilize the Eonia in the crisis. Second, according to the large and significant estimates for β the main information revealed by MRO auctions is now contained in the spread between the MRO rates $(r_w - r_m)$ and not in their levels.

During the crisis, huge MRO spreads inflated by safety bids stirred by banks' uncertainty about their refinancing conditions increased the Eonia and exacerbated the disconnection of money market rates from the policy-intended interest rate level. In sharp contrast to their stabilizing effect before the crisis, the outcomes of MRO auctions thus contributed to destabilize money market rates. In a vicious circle, a large MRO spread increased the Eonia, impaired banks' refinancing conditions and hence created even higher MRO spreads. In view of these problems, our empirical results strongly support the ECB's decision to re-stabilize banks' refinancing conditions by introducing a fixed rate full allotment policy in its MROs as of October 2008.

Probably reflecting the decreasing role of the main refinancing rates, the estimated adjustment equation of the Eonia indicates a growing importance of the liquidity volumes allotted in the MRO auctions. According to the estimates, an increase in the cover-to-bid ratio CBR by 10 percentage points would lower the Eonia by roughly 2.5 basis points. Note that a stronger effect on the Eonia can also be observed for the number of bidders.

3.4.3 MRO Auctions and Longer-Term Interest Rates during the Crisis

In October 2008, the ECB stopped the destabilizing effect of the MRO spread by switching the MRO auction format from variable rate to fixed rate tenders with full allotment. In a fixed rate tender with full allotment, all information about the MRO-related refinancing conditions is already pre-announced. The new auction format ensures that the cover-to-bid ratio equals one and that the MRO spread is zero by construction. According to our estimates for Eonia, both measures have contributed to improve banks' refinancing conditions.

However, the ECB took additional, even more unconventional measures to stabilize the situation in the money market. Before the crisis, the ECB was very reluctant to give strong signals about the policy-intended level of longer-term money market rates. As a consequence, longer-term refinancing operations (LTROs) have always been conducted as variable rate tenders without a minimum bid rate, see Linzert et al. (2007).

Since October 2008, however, the fixed rate full allotment policy has been also applied to the ECB's longer-term refinancing operations.

Table 13: Longer-Term Money Market Response to an MRO Outcome during the Crisis

Auction Variables	Response of longer-term money market rates (Δi_t) $\Delta i_t = c + \alpha(r_m - i_b)_t + \beta(r_w - r_m)_t + \gamma_C CBR_t + \gamma_B B_t + \gamma_A \Delta AF_t + \epsilon_t$			
	Crisis: August 2007 - June 2008			
	1–Month Eonia Swap Rates	3–Month Eonia Swap Rates	6–Month Eonia Swap Rates	12–Month Eonia Swap Rates
$(r_m - i_b)$	-0.0050 [0.0400]	0.0582 [0.0460]	0.0570 [0.0528]	0.0425 [0.0426]
$(r_w - r_m)$	0.5848*** [0.1829]	0.6537** [0.2589]	0.7844** [0.3213]	1.3251** [0.5366]
Cover-to-Bid Ratio (CBR)	-0.1341*** [0.0304]	-0.0868*** [0.00313]	-0.0669 [0.0570]	-0.1458* [0.0866]
Number of Bidders (B)	0.0002** [0.0001]	0.0003*** [0.0001]	0.0002* [0.0001]	0.0005** [0.0002]
Autonomous Factors (ΔAF)	0.0001 [0.0003]	0.0003 [0.0004]	0.0001 [0.0005]	-0.0002 [0.0008]
Obs.	33	33	33	33
R^2	0.53	0.35	0.21	0.25

Notes: For further explanations, see Table 12.

Moreover, while the maximum maturity of LTROs was three month before the crisis, the ECB additionally introduced LTROs with maturities of one, six and even twelve months. In order to shed more light on the rationale behind these measures, we investigate whether the destabilizing effects of MROs observed for the Eonia can also be found for longer-term money market rates. To that aim, we adopt the empirical approach of the previous sections and regress the change of longer-term Eonia swap rates at an auction day on the variables characterizing the MRO auction outcome.

The Eonia swap market is the most important derivative market segment in the euro area, see Durré (2006). The change of the Eonia swap rate at the auction day should reflect the impact of the auction outcome on market's expectations about future Eonia rates, see Taylor and Williams (2009). The results obtained for the swap rates are very similar to those obtained for the Eonia for all maturities under consideration, compare Table 12 and Table 13. In particular, there is clear evidence suggesting the absence of a stabilizing level relationship between the longer-term money market rates and the MRO rates, i. e. $\alpha = 0$. As expected, longer-term money market rates react more strongly to news about the future path of short-term rates and less to the current level. It is more striking, however, that large MRO spreads $(r_w - r_m)$ led also to significant and presumably policy-unintended increases of the longer-term money market rates, i. e. $\beta > 0$.

It is well-known that interest rate expectations affect the bidding behavior and, thereby, the results of MRO auctions, see e. g. Bindseil et al. (2009). However, Table 13 shows that - vice versa - MRO auctions can reveal information that may also affect banks' interest rate expectations. The significant response of longer-term swap rates suggests that the large MRO spreads observed until October 2008 even destabilized longer-term money market rates. These results provide strong support for the ECB's switch to the fixed rate full allotment policy even in its longer-term refinancing operations.

3.5 Conclusion

The interest rates applied in the main refinancing operations (MROs) of the ECB constitute the starting point of the monetary transmission process in the euro area. For the implementation of monetary policy, the connection between main refinancing rates and short-term interest rates in the money market is of particular importance. In line with their predominant role for monetary policy implementation, the results of MRO auctions should have a strong and stabilizing impact on money market conditions. This paper assessed the empirical relationship between MRO auctions and the money market by investigating the response of money market rates to MRO auction outcomes.

Our results show that the financial crisis distorted the relationship between MROs and the money market in two important ways. First, we find that the level of money market rates has been disconnected from MRO rates since the outbreak of the crisis in August 2007. In contrast to the pre-crisis period, MRO auction outcomes fail to stabilize money market rates during the financial crisis. This implies that the first step of the transmission channel of monetary policy has been interrupted.

The second change in the relationship between MRO auctions and the money market concerns the role of the MRO spread, i. e. the difference between the weighted average and the marginal MRO rate. While MRO spreads have been typically small before the crisis, in the crisis MRO spreads were inflated by safety bids reflecting the increased uncertainty of banks about their refinancing conditions. In contrast to the stabilizing impact of MRO auctions before the crisis, the response of money market rates to the MRO spreads destabilized money market conditions by exacerbating the disconnection of money market rates from the policy-intended interest rate level. This self-enforcing destabilization is also found for longer-term money market rates. Both findings strongly support the ECB's decision made in October 2008 to re-stabilize banks' refinancing conditions by adopting a fixed rate full allotment policy in its MROs and also in its longer-term refinancing operations (LTROs).

The ECB has repeatedly emphasized that the conduct of MROs as ‘fixed rate tenders with full allotment’ can only be a temporary measure in response to the financial crisis, see e. g. European Central Bank (2010). How should the ECB perform its MRO auctions after the crisis? According to the empirical auction literature the optimal choice of the auction format is not obvious. In particular, the ECB experienced that the rationing of bids in a fixed rate tender *without* full allotment led to an escalating overbidding problem, i. e. banks increasingly exaggerated their bid volumes to circumvent the rationing, see Nautz and Oechssler (2006). In June 2000, the ECB stopped banks’ overbidding by switching to a price-discriminatory variable rate tender format. Since successful banks ‘pay what they bid’, the effective refinancing rate differs across banks. This paper demonstrated that - particularly in times of market stress - large MRO spreads, defined as the difference between the weighted average and marginal MRO rate, may destabilize money market rates in a significant way. It is therefore worth noting that the price-discriminatory variable rate tender is not the only option of the ECB. In particular, the Dutch or competitive auction format as recently conducted by the Federal Reserve System in its term securities lending facility (TSLF) could be an alternative to the ECB’s standard variable rate tender, see e. g. Fleming et al. (2010). In the competitive auction format, the probably destabilizing MRO spreads are always zero because each successful bidder pays simply the marginal rate.

3.6 Appendix to Chapter 2

3.6.1 Structural Break Test

This section uses structural break tests to investigate whether the financial crisis had a significant impact on the relationship between the ECB's MRO auctions and the money market. To that aim, the Quandt-Andrews test for unknown breakpoints is applied to the error-correction type adjustment equation of the Eonia, compare equation (3.1):

$$\begin{aligned} \Delta i_t &= c + \alpha(r_m - i_b)_t + \beta(r_w - r_m)_t \\ &+ \gamma_C CBR_t + \gamma_B B_t + \gamma_A \Delta AF_t + \varepsilon_t \end{aligned}$$

We test whether there has been a break in the equation parameters c, α, β, γ_B, and γ_A for the full sample from June 27, 2000 to October 14, 2008.[39] The Quandt-Andrews test is based on standard F-statistics, see Andrews (1993). $Max\ F$ denotes the maximum of the individual *F*-statistics while the *Ave* statistic refers to their average. Since the break point is unknown, the asymptotic distribution of both test statistics are non standard and depend on the number of coefficients that are allowed to break and on the fraction of the sample that is examined.[40] Approximate asymptotic *p*-values are calculated following Hansen (1997).

The results confirm that the role of MRO auctions for the money market has significantly changed since the start of the financial crisis. For both, daily and intra-day data, the $Max\ F$ statistics chooses the first MRO auction after the outbreak of the crisis as the main candidate for a significant break point.

[39] Note that we already accounted a structural change in the role of CBR stirred by the reform of the ECB's operational framework as of March 2004. Therefore, we have excluded γ_C from the test.

[40] Note that the distributions become degenerate as the first period tested approaches the beginning of the equation sample, or the end period approaches the end of the equation sample. To compensate for this behavior it is generally suggested to exclude the end of the equation sample from the testing procedure. Following Andrews (1993), we apply a symmetric "trimming" of 5%.

Table 14: Quandt-Andrews Unknown Breakpoint Test

Statistic	Daily Eonia	Intra Day Data
Max F (08/09/2007)	19.06 [0.0556]	17.77 [0.0878]
Ave F	11.54 [0.0047]	13.22 [0.0012]

Notes: Estimated break date and approximate asymptotic p-values in line with Hansen (1997) in parenthesis. Test sample: June 27, 2000 to October 14, 2008 for daily Eonia and December 4, 2000 to June 17, 2008 for intra day data. Number of breaks compared: 318 and 284, respectively.

3.6.2 Forecast Equation of Number of Bidders

Following e. g. Bindseil et al. (2009) and Bindseil et al. (2007), we estimate the unexpected part in the number of bidders by regressing the number of bidders (B_t) in the current auction *t* on the number of bidders in previous auctions. With respect to the changes in seasonality and maturity in the ECB's operational framework as of March 2004, we estimate the forecast equations for each subperiod separately:

$$\begin{aligned} B_t^{OldFramework} &= \underset{(7.7)}{19.83} + \underset{(0.05)}{0.39} B_{t-1} + \underset{(0.05)}{0.52} B_{t-2} \\ &- \underset{(15.90)}{73.98} D_t^{Underbid} + \underset{(93.08)}{92.45} D_{t-1}^{Underbid} + \underset{(16.17)}{21.07} D_{t-2}^{Underbid}, \end{aligned} \tag{3.2}$$

with $R^2 = 0.86$ for the sample prior to March 2004 and

$$B_t^{NewFramework} = \underset{(27.54)}{101.61} + \underset{(0.08)}{0.72} B_{t-1}, \tag{3.3}$$

with $R^2 = 0.52$ after March 2004 until October 2008. Newey-West HAC standard errors are reported in parentheses. $D_t^{Underbid}$ is a dummy variable where $D_t^{Underbid} = 1$ captures the underbidding episodes that occurred in auction *t*.[41] The bi-weekly and weekly maturity of the MROs before and after March 2004, respectively, suggests the choice of the lag structure.

[41] The underbidding events refer to the MROs on 13 Feb, 10 Apr, 9 Oct and 6 Nov 2001, 3 Dec and 17 Dec 2002, 3 Mar, 3 Jun and 25 Nov 2003 and 20 Feb , see Bindseil (2004b).

Chapter 4

The Effectiveness of Monetary Policy in Steering Money Market Rates During the Financial Crisis

" How can we be sure that the long-term rate of interest will respond to the wishes of a currency authority which will be exerting its direct influence, as it must, mainly on the short-term rate"
(John Maynard Keynes, 1930)

4.1 Introduction

Since the middle of 2007, financial markets around the world have been severely impaired. In particular, money markets have contracted substantially causing serious disruptions in banks' short-term funding. As a result, unsecured money market rates have risen to unprecedented levels leading to a tightening of credit standards for both businesses and households, see European Central Bank (2007b). These developments have called into question that monetary policy can effectively steer term money market rates in such an environment. In order to shed more light on this issue, this paper focuses on two aspects. First, it explores the predictability of money market rates on the basis of monetary policy expectations. And second, it studies the impact of the ECB's crisis-related (non-standard) monetary policy measures on money market rates.

The euro area financial system has a bank-centered structure and, as such, unsecured money market rates determine short-term bank loan and deposit rates and thereby financing conditions for households and businesses. The euro interbank offered rate (Euribor), in that respect, is the standard reference rate for the unsecured money market and serves as the benchmark for the pricing of fixed-income securities throughout the economy. Moreover, short-term retail bank interest rates are priced in relation to the Euribor, and mortgage rates are often even indexed to it, see de Bondt et al. (2005), Sorensen and Werner (2006). Therefore, the prevailing Euribor rate plays a key role for the effectiveness of monetary policy and the functioning of the transmission mechanism in the euro area.

According to the expectation hypothesis, the current structure of term money market rates contains an implicit path of the expected future short-term interest rate, i.e. the policy rate set by the central bank, see e. g. Campbell and Shiller (1991), and Rudebusch (1995). This path reflects how interest rates will evolve over time and how they will change if new information about the economic outlook and monetary policy necessitate a revision of the path. The ECB's communication management seeks to ensure that uncertainty around this central scenario remains well contained, compare European Central Bank (2006). Hence, for effectively steering money market rates, it is crucial that interest rate expectations are in line with the central bank's policy intentions and that the dispersion of market expectations is kept at the lowest level possible. Within a univariate model framework of the three-month (3M), six-month (6M), and twelve-month (12M) Euribor rate, we will evaluate the effectiveness of ECB's monetary policy in steering these rates throughout the financial crisis.

Our results can be summarized as follows. Before the financial crisis, Euribor rates were in line with monetary policy expectations up to the twelve-month maturity bucket. During the financial crisis, the Euribor rates appear to deviate strongly from the central path expected by market participants for monetary policy. In fact, while the relationship is slightly relaxed during August 2007 and October 2008, it becomes weak in the period after October 2008. In the period until October 2008, uncertainty around the central path of monetary policy expectations seems to contribute to a widening of Euribor rates. The results indicate that this dispersion in market expectations, in turn, can partly be explained by elevated risk measures but mostly by the outcome of ECB's main refinancing operations. Furthermore, we find that the difference between the weighted average rate and the marginal MRO rate increases uncertainty around the expected path of future monetary policy. After October 2008, when the ECB switched its auction format, uncertainty seems to play no significant role for Euribor rates. Rather, money market rates have become severely persistent, i.e. shocks will last longer in Euribor rates and may thereby impede their controllability. That might explain why, during the crisis, the central path of monetary policy expectations could not be clearly reflected in Euribor rates. Our results also indicate that until October 2008, liquidity premia were most severe while both liquidity and credit concerns are found to have increased Euribor rates in the period after October 2008. Furthermore, our results provide strong evidence that the ECB's crisis-related (non-standard) monetary policy measures were highly effective in reducing Euribor rates and the uncertainty around the prevailing term money market rates. In fact, according to our estimates the significant increase in the net volume of outstanding open market operations as of October 2008 caused Euribor rates to decline for more than 60 basis points.

The empirical literature has analyzed the transmission of monetary policy in the euro area through various lenses. Most papers have focused on the effectiveness and relative importance of different transmission channels over the cycle, see e. g. Chatelain et al. (2003), Ehrmann et al. (2003), Peersman and Smets (2003)), whereas other contributions have studied the asymmetric functioning of channels during upswings and downswings, see e. g. Bean et al. (2003), Ehrmann and Worms (2004), Eickmeier et al. (2006). However, the effectiveness of monetary policy during significant crises, and especially during the recent financial crisis has not been sufficiently investigated yet.

The remainder of the paper is organized as follows. The next sections briefly elaborates on the role of the euro area term money market for the monetary transmission process. Section 4.3 covers the expectations hypothesis. Section 4.4 discusses the variables that might determine the dynamic of Euribor rates and Section 4.5 presents our empirical model. In Section 4.6, we show our empirical results and Section 4.7 concludes.

4.2 Euribor Rate and the Monetary Transmission Mechanism

In order to achieve its primary objective of price stability, the European Central Bank (ECB) aims at steering money market interest rates. For its effectiveness different channels are viewed to be essential.[42] The key feature to many of these mechanisms is the entire expected path of interest rates: it affects the cost of lending to households and companies, the level of economic activity and price stability. The yield curve of interest rates itself is predominantly shaped by the economic agents' expectations about monetary policy. Therefore, anchoring these expectations is key for a monetary policy that aims at steering interest rates to facilitate the transmission process, see Woodford (2003).

For the transmission mechanism of monetary policy, a particular role has been assigned to the unsecured segment of the money market. This part of the market covers the highest lending and borrowing activities in the euro area interbank market. For this segment, the Euribor rate reflects the interest rate at which European banks provide uncollateralized short-term loans to one another.[43] The maturities at which these unsecured loans are traded range from one week to twelve months. The longer-term maturity bucket, especially the three-month Euribor rate, is used

[42] For a detailed discussion of these transmission channels, see e. g. Mishkin (1995) and Bean et al. (2003). Boivin et al. (2010) review the core channels of policy transmission and provide new insights on how the transmission mechanism might have evolved in recent decades.

[43] Since money market transactions are carried out on a bilateral basis, they are notoriously hard to obtain. Therefore, established reference rates such as the Euribor serve as the best (available) proxy for actual transactions in the unsecured segment of the money market. See also www.euribor.org for further details.

as the basis for the settlement of various interest rate contracts, like interest rate swaps and futures. But when banks provide funding through mortgages they also tie the mortgage interest rate to the Euribor rate. A party who engages in a mortgage contract with a floating rate agrees to pay the Euribor rate plus a fixed commission, i.e. Euribor + x%. So, an increase in the Euribor rate will most likely be followed by a rise in the mortgage interest rate. In many European countries, the movement of the Euribor rate serves also as the benchmark for the interest rate offered on savings accounts. This is because deposits are also a way of borrowing liquidity. The interest rate offered to those holding a savings account is in many cases lower than the Euribor rate so as to allow a margin for the bank. Hence, when the Euribor rate declines, the bank's margin will decrease accordingly. So, banks will also adjust the interest rates on savings accounts downward.[44] Given the broad influence of the Euribor rates, it is of crucial importance that these rates correctly reflect the expectations of the monetary policy intentions. The specific relationship between longer-term money market rates and the expected future overnight rate over the same horizon is best described by the expectations hypothesis, which is explained in the next section.

4.3 Expectations Hypothesis

From a theoretical perspective, the (weak) form of the expectations hypothesis of the term structure states the equality between current longer-term rates and the average expected overnight rate plus a constant maturity specific risk premium, see e. g. Litterman et al. (1991) and Hamilton and Kim (2002).[45] In a first-difference representation of the respective longer-term interest rate, R, of duration k, the relationship can be written as:

[44]Note that this adjustment often happens with a delay because the interest rate offered by many banks on savings is only altered when there has been an interest market change of some magnitude.

[45]We consider the weak form of the expectations hypothesis to be the relevant form. The strong view without a premia conflicts with the fact that yield curves normally slope upwards, which would imply that short-term rates are expected to trend upwards infinitely.

$$\Delta R_t(k) \quad = \quad \alpha \left(\frac{1}{k} \sum\nolimits_{j=0}^{k-1} \Delta E_t(r_{t+j}) \right) \tag{4.1}$$

where Δ and E_t denote the first-difference and expectations operator, respectively, at time t. The advantage of expressing the model in first differences is twofold. First, it relaxes the assumption of perfect foresight, and second, it avoids potential issues of non-stationarity associated with interest rates, see Appendix.[46] In Equation (4.1), α captures the relationship between the change in the current longer-term rate of duration k and changes in the average expected overnight rate over the same horizon, i.e. $\frac{1}{k} \sum_{j=0}^{k-1} \Delta E_t(r_{t+j})$.[47] In the level representation of Equation (4.1), the expectations hypothesis requires a theoretical one-to-one relationship for it to hold, i. e. $\alpha = 1$. But in the first-difference specification, a coefficient estimate of (statistically) less than one need not to point to a failure of the hypothesis, see Kuttner (2001). He argues that changes in current longer-term rates on the day of a policy rate change announcement reflect changes in the average expected overnight rates over the duration of the contract. Therefore, the impact of a one-day surprise may be less than one-for-one.[48] Furthermore, Demiralp and Jorda (2004) show that many one-day policy steps have to do with the timing of the action rather than with their ultimate size.

4.4 Variables and Predictions

4.4.1 Market Expectations

The overnight indexed swap (OIS) rate is per construction a good tool to assess the *central path* expected by market participants for monetary policy. In the euro area, it is the main instrument used by market participants to take speculative

[46]The assumption of perfect foresight states that $E_t(i_{t+j}) = i_{t+j}$, where i denotes the overnight interest rate, see e. g. Mankiw and Miron (1986) and Campbell and Shiller (1991).

[47]For long-term interest rates beyond the 10 year horizon, the Jensen's inequality term arises because a log of an expectation does not equal the expectation of a log. At our maturities, however, this term is rather negligible and hence needs no further consideration for our analysis.

[48]See Demiralp (2008) for an empirical evidence on the 3M Treasury Bill rate.

positions on expected central bank actions. It reflects the average short-term rate that economic agents expect to prevail over the next k days. Hence, changes in the European OIS rate would suggest revisions in expectations of future overnight rates over the course of the correspondingly dated Euribor rate. In Equation (4.1), we would measure $\frac{1}{k}\sum_{j=0}^{k-1}\Delta E_t(r_{t+j})$ by $\Delta OIS_t(k)$. And if monetary policy expectations actually shape Euribor rates, α should be significant and positively signed.[49]

But the OIS rate does not give any indication on the *uncertainty* in market expectations *around* this central scenario. For instance, uncertainty may arise when market participants either do not actually understand monetary policy or simply misperceive future interest rate decisions, see Nautz and Schmidt (2010). In particular, uncertainty is very likely to emerge in an environment of market stress. To assess the uncertainty associated with expectations of future interest rates, we use the implied volatility of option prices on Euribor futures as they are traded at the London International Financial Futures Exchange (LIFFE).[50] Option prices rely upon the volatility of the underlying asset, i.e. upon Euribor futures in our case. In the futures market, even tiny moves are tradable. This implies a very sensitive measure of interest rate expectations. The volatility of Euribor futures is, in turn, closely linked to the volatility of Euribor rates given the linear relationship between these two series at final settlement, i.e. $F_t(k) = 100 - R_t(k)$ where $F_t(k)$ denotes the Euribor futures contract. If the central bank is effective in keeping the uncertainty in market expectations well contained, the Euribor rates should not respond to options implied volatility on Euribor futures.

[49]Since March 2008, the announcement of OIS rates has changed from 4:30 p. m. CET to 11 a. m. CET. In line with the fixing of the Euribor, the definition of $\Delta OIS_t(k)$ is adjusted accordingly.

[50]These contracts account for over 90% of euro-denominated short-term interest rate trades with an average daily volume of roughly 1,000,000 contracts.

4.4.2 Risk Measures

The common approach in the expectations hypothesis literature is to include a constant term in the level-representation of Equation (4.1), which is argued to capture the time-invariant term premium. Under the assumption that this premium is constant over time, it cancels out in a first-difference representation. During a financial crisis, as we are currently witnessing, the premium may not only be significant in size but may also change substantially from one day to another. Therefore, a model of longer-term interest rates throughout the crisis should incorporate time-variant risk measures.

During the recent financial crisis, there have been different forms of risk at play: *liquidity risk* (Eisenschmidt and Tapking, 2009), *credit risk* (Taylor and Williams, 2009), and the *combination* of both risks mutually reinforcing each other (McAndrews, Sarkar and Wang 2008, Abbassi and Schnabel 2009, Brunnermeier 2009, Brunnermeier and Pedersen 2009, Christensen, Lopez and Rudebusch 2009, and Schwarz 2010). In the attempt to derive an accurate measure for each of the additive forms of risk in longer-term interest rates, the following two approaches have been suggested. On the one hand, one may assume that the risk component in Euribor rates is fully explained by a liquidity and a credit part. However, volatility effects of future expected overnight rates are ignored completely (e. g. Michaud and Upper (2008)). Therefore, this specification is likely to bear the problem associated with omitted variable bias. On the other hand, one may use a two-step approach following the logic of the partitioned regression analysis. This would enable a decomposition of risk premia into e. g. a credit and a non-credit part. That approach implicitly assumes orthogonality between the two risk factors. But during the ongoing crisis, it is very likely to believe that these risk factors mutually affect and even reinforce each other, see Brunnermeier and Pedersen (2009) and Brunnermeier (2009). Therefore, using the latter approach would bias one of the estimated coefficients of the risk variables by misleadingly allocating the joint variation of the considered risk measures to one of the decomposed risk elements. For our analysis, we will therefore use the former approach since we already control for uncertainty in expectations around the central path of monetary policy expectations.

Our risk variables are as follows. Longstaff (2004) argues that the spread between the Resolution Funding Corporation (Refcorp) and U.S. Treasury bonds is an accurate measure of Treasury market liquidity. In the same vein, we construct the spread between the Kreditanstalt für Wiederaufbau (KfW) and German federal government bonds to account for (market) liquidity premia investors demand in the German government bond market. Bonds, in general, are debt securities generating identical cash flows in all states of the world. Also, KfW agency and German federal government bonds have the identical credit profile as they are backed by the full faith and credit of the German fiscal authority. In fact, the German fiscal authority explicitly guarantees all KfW's current and future obligations.[51] In that sense, there is no credit risk attached. However, KfW agency bonds are less liquid than their federal government counterparts.[52] The spread between these bonds, therefore, captures the investors' demanded premium for present and expected transaction costs and for the risk of liquidity deterioration. In contrast to the unsecured segment of the money market, the sovereign debt market represents an environment in which there is negligible counterparty risk reflected in transaction prices that are agreed upon before the identity of the counterparty is even known.[53] Our spread reflects more precisely market liquidity in the money market than traditional variables such as bid-ask spreads derived from interbank rates, see also Schwarz (2010). Since Euribor rates refer to the unsecured segment of the money market, higher values of our KfW spread should lead to an increase in Euribor rates.[54]

[51]See www.kfw.de/en for details.

[52]Even though they are less liquid, the bonds are traded sufficiently enough to allow high frequency observations, see Chordia et al. (2005).

[53]This, however, might not be the case for all bonds during the recent sovereign debt crisis. But, to avoid that our analysis is driven by the recent sovereign debt crisis, we have excluded the sample after 2010 from our analysis.

[54]Note that this approach implicitly assumes that our (market) liquidity measure is proportional to the liquidity premium in the money market.

As our credit risk measure, we use the 5-year iItraxx Europe Senior Financials. This is an index created as a portfolio of single-name credit default swaps (CDS). It consists of the most liquid CDS contracts of the 25 largest financial names headquartered in Europe. A dealer poll selects these names based on CDS volumes traded over the previous six months. New series of the iTraxx index are typically issued every six months. A CDS, in general, isolates per construction the credit risk component from other potential risks, such as interest rate risk and foreign exchange risk as investors buy pure credit risk, see Byström (2005). Another important feature of such a credit derivative is that credit risk is transferred without any funding actually changing hands. Funds are only provided ex post, in case a credit event occurs. High values of the iTraxx index are therefore an indication of high credit risk in the euro area financial sector. Thus, we would expect that this shifts Euribor rates upward.

4.4.3 Central Bank Measures

High levels of interest rates may have serious implications for monetary policy: they put the clarity with which monetary policy intentions are reflected in the shape of the yield curve at risk. As a response to the tensions surrounding the money market after mid 2007, the ECB mainly increased its liquidity provision. In order to make this liquidity provision equivalent to borrowing at the Euribor rate, the ECB extended the horizon of the open market operations from three months to six months and twelve months.[55] Until October 2008, the ECB rearranged its allotment pattern in its main refinancing operations (MROs) and extended its liquidity provision in size and frequency through supplementary longer-term refinancing operations (LTROs), albeit overall liquidity provision was kept more or less unchanged. After October 2008, the ECB's balance sheet grew considerably in size due to a number of extraordinary measures including a fixed-rate unlimited

[55]Note that these two markets are no direct substitutes as, in contrast to the unsecured money market, banks need to post collateral in the ECB's open market operations. But one may argue that this should not be a serious constraint as the ECB has accepted almost any asset as collateral since the onset of the crisis, see Giavazzi (2008).

liquidity provision and a further broadening of refinancing horizons.[56] If the rearrangement and the widening of the liquidity supply helped to reduced the strains in the money market, Euribor rates should decrease with increasing liquidity provision.

But for the period before 2007, it is not clear whether Euribor rates should respond to MROs. The ECB publishes its calculations of the benchmark liquidity allotment before each operation such that the allotment volume can be anticipated fairly accurately by the banks.[57] There is, in general, also no reason to believe that the liquidity supply through LTROs should impact Euribor rates prior to mid 2007. First, these longer-term operations did not matter in size. And second, the liquidity allotment amount was fixed and pre-announced.

As part of its weekly financial statement, the ECB announces its net lending associated with its monetary policy operations to credit institutions. The *outstanding volumes* of both the MROs and the LTROs are therefore a natural variable representing the size of the ECB's liquidity provision. In order to measure excessive liquidity (provision), one may be tempted to rather use the recourse to the net deposit facility. But until October 2008, overall liquidity provision was kept more or less unchanged, see European Central Bank (2010). Hence, we only observe an increase in banks' recourse to the deposit facility as of October 2008. Nevertheless, while it is reasonable to think that the usage of the deposit facility will affect the Eonia - as both have overnight maturity - it is far from obvious why it should affect longer-term interest rates, in particular beyond the respective reserve maintenance period. Against this background, we believe that our measure "outstanding volumes" is more appropriate as is reflects (i) liquidity supply in general, (ii) ECB's change in allotment pattern, and (iii) all respective maturities (1W, 3M, 6M, 12M) at the same time.

Furthermore, the *announcement* of each (non-standard) operation may affect Euribor rates. Standard open market operations (OMOs) are announced in an annual

[56] Additionally, the ECB established a foreign currency funding facility, notably in U.S. dollars.

[57] The benchmark allotment constitutes a baseline for the ECB when making its actual allotment decision, see European Central Bank (2004b).

indicative calendar three months before the year for which they are valid. Therefore, we will only consider announcement effects related to non-standard refinancing operations (sLTRO) during the crisis period. If the announcement had a relieving impact on the money market rates, the expected signs of the coefficients would be significant and negatively signed.

4.5 Modeling the Euribor Dynamics

Following the rationale of the expectations hypothesis, we specify the following model for the Euribor rate based on the aforementioned variables.[58]

$$\begin{aligned}
\Delta R_t(k) &= \sum\nolimits_{i=1}^{3} \alpha_{1,i} D_{t,i} \Delta OIS_t(k) + \sum\nolimits_{i=1}^{3} \alpha_{2,i} D_{t,i} \Delta IV(F_t) \\
&+ \sum\nolimits_{i=1}^{3} \beta_{1,i} D_{t,i} \Delta itraxx_t + \sum\nolimits_{i=1}^{3} \beta_{2,i} D_{t,i} (KfW - bund)_t \\
&+ \sum\nolimits_{i=1}^{3} \gamma_i D_{t,i} (\Delta OMO_t / OMO_{t-1}) + \gamma_4 D^{an}_{sLTRO\ 3M} \\
&+ \gamma_5 D^{an}_{sLTRO\ 6M} + \gamma_6 D^{an}_{sLTRO\ 12M} + \sum\nolimits_{i=1}^{3} \sum\nolimits_{j=1}^{5} \varphi_{i,j} D_{t,i} \Delta R_{t-j}(k) \\
&+ \delta' X_t + \epsilon_t \qquad (4.2)
\end{aligned}$$

where k denotes the respective maturity and Δ the first-difference operator. We will focus on the 3M, 6M, and 12M Euribor rate. OIS captures the correspondingly dated OIS rate. We do not impose the expectations hypothesis on our estimation. In fact, in order to investigate whether the link between Euribor rates and market's monetary policy expectations has changed during the crisis, we need to estimate α. IV refers to the options' implied volatility of the 3M Euribor futures (F_t). OMO captures the sum of outstanding volumes associated with the MROs

[58] Alternatively, one may use the Italian electronic trading platform e-Mid that accounts for 17 % of all transactions in the shortest-maturity segment of the unsecured European money market. However, since trades are executed in full transparency, this platform will rather be used by "good" banks. Thus, data collected from e-Mid should not vary much, in particular in times of crises, from the Euribor rates which themselves are based on a panel of prime banks with the highest credit standards in the euro area. Please refer to Angelini et al. (2009) for an illustration of both data sources.

and LTROs.[59] D^{an}_{sLTRO} is a dummy variable that equals one for all days on which an sLTRO was announced and zero otherwise.[60] X reflects a vector of dummies controlling for calendar effects in the data. For instance, liquidity pressures in money markets may arise due to end-of-year window dressing of balance sheets by financial institutions. Along the lines of Hassler and Nautz (2008) and Busch and Nautz (2010), controllability of money market rates requires sufficiently low persistence in longer-term money market rates. If money market rates are too persistent, the lasting impact of shocks can impede the transparency of policy signals and the central bank's influence on money market rates along the yield curve. Hence, we also control for the persistence in Euribor rates by $\sum_{j=1}^{5}\varphi_j$.[61]

Our sample covers the period from 16 June 2004 through 31 December 2009.[62] The Euribor rates may respond differently before and after August 2007 and October 2008, respectively. To take this into account, we define D_1 to be the dummy variable for the sample period from June 2004 to August 2007. Accordingly, we define two further dummy variables where one accounts for the period before (D_2) and another for the sample after (D_3) October 2008. The results obtained for the 3M, 6M, and 12M Euribor rate are presented in Table 15, 16 and 17, respectively.

[59]Note, however, that this procedure is not sufficient to identify the causal effects of central bank actions. Rather, it measures interest rate movements immediately after central bank actions.

[60]Note that for this analysis, modeling our equation of the Euribor in first differences is the most appropriate approach. A level representation would implicitly assume that the (liquidity) risk premium that might fall on a day of the actual operation will revert to the previous level immediately after the operation. However, if the liquidity premium remains at the lower level over many days after an operation, the estimated coefficient of the event cannot be interpreted as a central bank effect and it would likely appear insignificant.

[61]Since we use daily observations, a lag order of five days seems reasonable. This is also suggested by the AIC information criteria.

[62]Before June 2004, there is no series of the iTraxx index available. The period excludes the sample covering the recent sovereign debt crisis. The analysis of the effects of the sovereign debt crisis on the behavior of Euribor rates is left for future research.

4.6 Effectiveness of Monetary Policy: Empirical Results

4.6.1 Response of the Euribor Rate to its Determinants

Steering Euribor Rates: Monetary Policy Expectations and Uncertainty Before August 2007, the estimated coefficient of the OIS rate ($\hat{\alpha}_{1,1}$) indicates for all three interest rate maturities a highly significant adjustment of the Euribor rate to monetary policy expectations. According to our results, a change of the OIS rate by 25 basis points (magnitude of an usual policy rate change) will cause the 3M, 6M and 12M Euribor rate to rise within a day by 6, 13 and 17 basis points, respectively.[63] This result is strongly consistent with the view that monetary policy expectations affect longer-term money market rates. Since mid 2007, the estimation results obtained for the coefficient $\alpha_{1,2}$ indicate a significant adjustment of the Euribor rates only until October 2008. Wald tests confirm that the response of the Euribor rate has changed significantly compared to the pre-crisis sample. For the period after October 2008, we find no significant adjustment coefficient, compare $\hat{\alpha}_{1,3}$. These results indicate that Euribor and OIS rates have been significantly diverging since August 2007.

Our coefficient $\hat{\alpha}_{2,1}$ suggests that uncertainty in market expectations did not affect Euribor rates before August 2007. During the crisis, however, the Euribor rate adjusts by 21, 22, and 15 percent ($\hat{\alpha}_{2,2}$), respectively, to changes in the options implied volatility on Euribor futures since mid 2007. After October 2008, the uncertainty appears to have no significant impact on Euribor rates.[64] This finding implies that the market was uncertain about the central path of monetary policy intentions during the period August 2007 and October 2008.

[63]Note that we relaxed the the assumption of the constant premia. Hence, the expectation hypothesis no longer attributes *all* changes in the yield curve solely to changes in expected short rates.

[64]We will investigate this issue in more detail below.

Table 15: Dynamics of the 3-Month Euribor Rate

Dependent Variable: $\Delta R_t(k = 3M)$					
Monetary Policy Expectations			*Uncertainty in Market Expectations*		
$\alpha_{1,1}$	Jun 2004 - Aug 2007	0.257^{***} (2.63)	$\alpha_{2,1}$	Jun 2004 - Aug 2007	-0.004 (0.23)
$\alpha_{1,2}$	Aug 2007 - Oct 2008	0.125^{**} (2.01)	$\alpha_{2,2}$	Aug 2007 - Oct 2008	0.207^{**} (2.16)
$\alpha_{1,3}$	Oct 2008 - Dec 2009	0.035 (1.72)	$\alpha_{2,3}$	Oct 2008 - Dec 2009	0.004 (0.51)
Credit Risk			*Liquidity Risk*		
$\beta_{1,1}$	Jun 2004 - Aug 2007	0.011 (0.27)	$\beta_{2,1}$	Jun 2004 - Aug 2007	0.195^{**} (2.38)
$\beta_{1,2}$	Aug 2007 - Oct 2008	0.109 (0.68)	$\beta_{2,2}$	Aug 2007 - Oct 2008	0.276^{***} (3.25)
$\beta_{1,3}$	Oct 2008 - Dec 2009	0.214^{***} (2.74)	$\beta_{2,3}$	Oct 2008 - Dec 2009	0.063^{*} (1.75)
OMOs (outstanding vol.)			*CB Measures: Ann. Effect*		
γ_1	Jun 2004 - Aug 2007	0.017 (1.19)	γ_4	Ann. of 3M sLTROs	-0.026^{**} (2.18)
γ_2	Aug 2007 - Oct 2008	-1.338^{**} (1.98)	γ_5	Ann. of 6M sLTROs	0.004 (1.04)
γ_3	Oct 2008 - Dec 2009	-1.571^{***} (2.67)	γ_6	Ann. of 12M sLTROs	-0.022^{***} (2.64)
Persistence					
$\sum_{j=1}^{5} \varphi_{1,j}$	Jun 2004 - Aug 2007	0.105^{**} (2.22)			
$\sum_{j=1}^{5} \varphi_{2,j}$	Aug 2007 - Oct 2008	0.529^{***} (6.64)			
$\sum_{j=1}^{5} \varphi_{3,j}$	Oct 2008 - Dec 2009	0.749^{***} (8.26)			
Calendar Dummies			*Crisis Dummies*		
δ_{eoq}	End of Quarter	0.012 (0.46)	δ_1	Aug 2007 - Oct 2008	0.504^{***} (3.08)
δ_{eos}	End of Semester	0.023^{**} (2.12)	δ_2	Oct 2008 - Dec 2009	0.390^{***} (3.01)
δ_{eoy}	End of Year	-0.030^{**} (2.45)			
R^2		0.67	Obs.		1447

Wald test on parameter equality $\mathcal{H}_0 : \mathcal{D} = 0$			
$\mathcal{D}$:	p-value	$\mathcal{D}$:	p-value
$\alpha_{1,1} - \alpha_{1,2}$	0.025	$\alpha_{2,1} - \alpha_{2,2}$	0.003
$\alpha_{1,2} - \alpha_{1,3}$	0.017	$\alpha_{2,2} - \alpha_{2,3}$	0.004
$\beta_{1,2} - \beta_{2,2}$	0.000	$\beta_{1,3} - \beta_{2,3}$	0.001
$\gamma_1 - \gamma_2$	0.005	$\gamma_2 - \gamma_3$	0.115
$\sum_{j=1}^{5} \varphi_{1,j} - \sum_{j=1}^{5} \varphi_{2,j}$	0.000	$\sum_{j=1}^{5} \varphi_{2,j} - \sum_{j=1}^{5} \varphi_{3,j}$	0.000

Notes: The estimation model is presented in Equation (4.2). Estimation of basis of daily data. HAC consistent, absolute t-statistics in parenthesis. ***,**,* indicate significance at the 1%, 5%, 10% level. Wald statistics are presented as p-values.

Table 16: Dynamics of the 6-Month Euribor Rate

Dependent Variable: $\Delta R_t(k = 6\text{M})$					
Monetary Policy Expectations			*Uncertainty in Market Expectations*		
$\alpha_{1,1}$	Jun 2004 - Aug 2007	0.515^{***}	$\alpha_{2,1}$	Jun 2004 - Aug 2007	0.035
		(9.45)			(1.60)
$\alpha_{1,2}$	Aug 2007 - Oct 2008	0.223^{**}	$\alpha_{2,2}$	Aug 2007 - Oct 2008	0.221^{**}
		(2.49)			(2.03)
$\alpha_{1,3}$	Oct 2008 - Dec 2009	0.018	$\alpha_{2,3}$	Oct 2008 - Dec 2009	0.014
		(0.87)			(1.58)
Credit Risk			*Liquidity Risk*		
$\beta_{1,1}$	Jun 2004 - Aug 2007	0.025	$\beta_{2,1}$	Jun 2004 - Aug 2007	0.445^{**}
		(0.37)			(2.39)
$\beta_{1,2}$	Aug 2007 - Oct 2008	0.035	$\beta_{2,2}$	Aug 2007 - Oct 2008	0.319^{**}
		(0.20)			(2.37)
$\beta_{1,3}$	Oct 2008 - Dec 2009	0.788^{***}	$\beta_{2,3}$	Oct 2008 - Dec 2009	0.453^{**}
		(2.78)			(1.98)
OMOs (outstanding vol.)			*CB Measures: Ann. Effect*		
γ_1	Jun 2004 - Aug 2007	0.020	γ_4	Ann. of 3M sLTROs	-0.009
		(1.17)			(0.25)
γ_2	Aug 2007 - Oct 2008	-1.098	γ_5	Ann. of 6M sLTROs	-0.017^{*}
		(0.91)			(1.91)
γ_3	Oct 2008 - Dec 2009	-1.037^{***}	γ_6	Ann. of 12M sLTROs	0.017
		(3.64)			(1.09)
Persistence					
$\sum_{j=1}^{5} \varphi_{1,j}$	Jun 2004 - Aug 2007	0.116^{***}			
		(3.18)			
$\sum_{j=1}^{5} \varphi_{2,j}$	Aug 2007 - Oct 2008	0.321^{***}			
		(3.42)			
$\sum_{j=1}^{5} \varphi_{3,j}$	Oct 2008 - Dec 2009	0.809^{***}			
		(12.08)			
Calendar Dummies			*Crisis Dummies*		
δ_{eoq}	End of Quarter	0.002	δ_1	Aug 2007 - Oct 2008	0.137^{***}
		(0.75)			(2.76)
δ_{eos}	End of Semester	0.016^{**}	δ_2	Oct 2008 - Dec 2010	0.349^{***}
		(2.21)			(2.89)
δ_{eoy}	End of Year	-0.078^{**}			
		(2.39)			
R^2		0.62	Obs.		1447

Wald test on parameter equality

$\mathcal{H}_0 : \mathcal{D} = 0$

$\mathcal{D}$:	p-value	$\mathcal{D}$:	p-value
$\alpha_{1,1} - \alpha_{1,2}$	0.005	$\alpha_{2,1} - \alpha_{2,2}$	0.009
$\alpha_{1,2} - \alpha_{1,3}$	0.009	$\alpha_{2,2} - \alpha_{2,3}$	0.006
$\beta_{1,2} - \beta_{2,2}$	0.000	$\beta_{1,3} - \beta_{2,3}$	0.007
$\gamma_1 - \gamma_2$	0.272	$\gamma_2 - \gamma_3$	0.005
$\sum_{j=1}^{5} \varphi_{1,j} - \sum_{j=1}^{5} \varphi_{2,j}$	0.000	$\sum_{j=1}^{5} \varphi_{2,j} - \sum_{j=1}^{5} \varphi_{3,j}$	0.000

Notes: The estimation model is presented in Equation (4.2). Estimation of basis of daily data. HAC consistent, absolute t-statistics in parenthesis. $^{***}, ^{**}, ^{*}$ indicate significance at the 1%, 5%, 10% level. Wald statistics are presented as p-values.

Table 17: Dynamics of the 12-Month Euribor Rate

Dependent Variable: $\Delta R_t(k=12\text{M})$					
Monetary Policy Expectations			*Uncertainty in Market Expectations*		
$\alpha_{1,1}$	Jun 2004 - Aug 2007	0.675^{***} (20.37)	$\alpha_{2,1}$	Jun 2004 - Aug 2007	0.033 (1.07)
$\alpha_{1,2}$	Aug 2007 - Oct 2008	0.236^{***} (2.76)	$\alpha_{2,2}$	Aug 2007 - Oct 2008	0.151^{***} (3.11)
$\alpha_{1,3}$	Oct 2008 - Dec 2009	0.019 (0.97)	$\alpha_{2,3}$	Oct 2008 - Dec 2009	0.028 (1.43)
Credit Risk			*Liquidity Risk*		
$\beta_{1,1}$	Jun 2004 - Aug 2007	−0.097 (0.77)	$\beta_{2,1}$	Jun 2004 - Aug 2007	0.526^{**} (2.17)
$\beta_{1,2}$	Aug 2007 - Oct 2008	0.057 (0.27)	$\beta_{2,2}$	Aug 2007 - Oct 2008	0.398^{***} (3.12)
$\beta_{1,3}$	Oct 2008 - Dec 2009	0.553^{**} (2.53)	$\beta_{2,3}$	Oct 2008 - Dec 2009	0.334^{**} (2.17)
OMOs (outstanding vol.)			*CB Measures: Ann. Effect*		
γ_1	Jun 2004 - Aug 2007	0.003 (0.90)	γ_4	Ann. of 3M sLTROs	0.040 (0.91)
γ_2	Aug 2007 - Oct 2008	−1.047 (1.10)	γ_5	Ann. of 6M sLTROs	0.007 (1.44)
γ_3	Oct 2008 - Dec 2009	-1.226^{***} (3.26)	γ_6	Ann. of 12M sLTROs	-0.059^{***} (2.91)
Persistence					
$\sum_{j=1}^{5}\varphi_{1,j}$	Jun 2004 - Aug 2007	0.087^{***} (2.57)			
$\sum_{j=1}^{5}\varphi_{2,j}$	Aug 2007 - Oct 2008	0.297^{***} (6.84)			
$\sum_{j=1}^{5}\varphi_{3,j}$	Oct 2008 - Dec 2009	0.772^{***} (10.27)			
Calendar Dummies			*Crisis Dummies*		
δ_{eoq}	End of Quarter	−0.001 (0.28)	δ_1	Aug 2007 - Oct 2008	0.338^{**} (2.35)
δ_{eos}	End of Semester	0.014^{*} (1.94)	δ_2	Oct 2008 - Dec 2010	0.403^{***} (2.90)
δ_{eoy}	End of Year	-0.153^{**} (3.57)			
R^2		0.53	Obs.		1447

Wald test on parameter equality
$\mathcal{H}_0 : \mathcal{D} = 0$

$\mathcal{D}$:	p-value	$\mathcal{D}$:	p-value
$\alpha_{1,1}-\alpha_{1,2}$	0.000	$\alpha_{2,1}-\alpha_{2,2}$	0.000
$\alpha_{1,2}-\alpha_{1,3}$	0.004	$\alpha_{2,2}-\alpha_{2,3}$	0.000
$\beta_{1,2}-\beta_{2,2}$	0.000	$\beta_{1,3}-\beta_{2,3}$	0.031
$\gamma_1-\gamma_2$	0.564	$\gamma_2-\gamma_3$	0.002
$\sum_{j=1}^{5}\varphi_{1,j}-\sum_{j=1}^{5}\varphi_{2,j}$	0.000	$\sum_{j=1}^{5}\varphi_{2,j}-\sum_{j=1}^{5}\varphi_{3,j}$	0.000

Notes: The estimation model is presented in Equation (4.2). Estimation of basis of daily data. HAC consistent, absolute t-statistics in parenthesis. $^{***},^{**},^{*}$ indicate significance at the 1%, 5%, 10% level. Wald statistics are presented as p-values.

Risk Measures and the Persistence of Euribor Rates Our estimates of the coefficients β_1 and β_2 show that risk premia affect Euribor rates in a significant way. While our estimation indicates that liquidity risk plays a significant role throughout our complete sample, credit concerns are found to have an impact on Euribor rates only during the period after October 2008. These results are consistent with the view that risk measures significantly contributed to an increase in Euribor rates.

Furthermore, Euribor rates are found to have very 'short memory' before the onset of the crisis. This low persistence in longer-term money market rates facilitates the ECB to effectively steer money market rates, see Busch and Nautz (2010). However, according to the large and significant estimates of $\sum_{j=1}^{5} \varphi_{2,j}$ and $\sum_{j=1}^{5} \varphi_{3,j}$, Euribor rates became severely persistent after mid 2007. In fact, we observe a threefold increase in persistence for the 3M, 6M, and 12M Euribor rates until October 2008. After October 2008, we even observe a fourfold, sixfold and 10-fold rise for the 3M, 6M and 12M rates, respectively. These estimates also suggest a change in the long-run dynamics during the period after mid 2007 but in particular after October 2008. For instance, the long-term effects of market's expectations on the 3M, 6M, and 12M Euribor before the crisis amounted to 0.29, 0.58, and 0.74, respectively. This changes slightly to 0.27, 0.33, and 0.34, respectively, during August 2007 and October 2008. But the most striking change is observed for the sample after October 2008: the long-run effects only account to 0.14, 0.09, and 0.08.[65] Hence, higher persistence of money market rates indicates that shocks may last longer. Moreover, this greater persistence in money market rates, in particular after October 2008, implies that it is more difficult for monetary policy signals to be transmitted through money market rates along the yield curve via conventional channels of monetary policy.

[65]The fact that there is a difference between short-term and long-term coefficients is a result of our specification which includes lagged endogenous variables. To illustrate this, let us consider our model in the following general representation: $y_t = c + \sum_{j=1}^{p} \varphi_j y_{t-j} + \theta' X_t + \epsilon_t$, where ϵ_t is an iid shock and X_t a vector of exogenous variables. Supposing that $E(y_t)$ and $E(X_t)$ are constant over time, our model can be rewritten as $E(y_t) = \frac{c}{1-\sum_{j=1}^{p} \varphi_j} + \left(\frac{\theta}{1-\sum_{j=1}^{p} \varphi_j}\right)' E(X_t)$ where the long-run relationship between y and X is thus given by $\frac{\theta}{1-\sum_{j=1}^{p} \varphi_j}$.

The ECB's liquidity provision In line with our expectations, Euribor rates do not significantly respond to percentage changes of the outstanding volume before the onset of the crisis. But our results strongly support the hypothesis that the ECB's net increase in outstanding open market operations helped to reduce Euribor rates: the estimated coefficients ($\hat{\gamma}_3$) are significant and negatively signed after October 2008. For the 3M Euribor rate, we also obtain a significant estimate ($\hat{\gamma}_2$) within the period August 2007 to October 2008. One may argue that the ECB's liquidity provision can only lower Euribor rates when the net volume of outstanding open market operations actually changes. Recall that until October 2008, the ECB rearranged the pattern and shares of its liquidity provision in the MROs and LTROs. But, compared to the pre-crisis period, the net volume remained unchanged at a level of € 450 billion. However, one may also argue that the rearrangement of the liquidity provision has established (some degree of) confidence that might have prevented Euribor rates from rising further, see e. g. Mishkin (2009). After October 2008, the ECB followed a policy of providing as much liquidity to euro area banking sector as demanded. As a result, the volume of outstanding refinancing operations increased significantly and peaked even to levels of around € 890 billion, see European Central Bank (2010). During our sample period, the amount of outstanding open market operation rose, in total, by more than 60%. According to our estimated coefficients $\hat{\gamma}_3$, this implies a reduction of the 3M, 6M, and 12M Euribor rate by more than 94, 62, and 73 basis points ($100 \cdot 0.6 \cdot \hat{\gamma}_3$), respectively.

Our findings also suggest that the announcement of the supplementary LTROs provided an important stimulus to the reduction of Euribor rates. For instance, the 3M Euribor rate shows to have been lower by roughly 2.6 ($\hat{\gamma}_4$) and 2.2 ($\hat{\gamma}_6$) basis points, respectively, at the days when 3M and 12M supplementary operations were announced. The announcement of 6M sLTROs are found to have reduced the 6M Euribor rate by roughly 2 basis points, while the 12M operation announcements lowered the 12M Euribor by roughly 6 basis points.[66]

[66] The full list of all announcements that we use for our analysis is available on `www.ecb.int/mopo/implement/omo/html/index.en.html#com`.

4.6.2 Uncertainty in Market Expectations

The previous section showed, inter alia, that uncertainty around the central path of monetary policy expectations explains a considerable part of the Euribor dynamics. This section investigates how the options implied volatility may be (at least partly) related to the institutional environment of the ECB's monetary policy framework. This is motivated by the findings presented in Chapter 3. It shows that the ECB's open market operation outcomes destabilized money market rates up to the twelve-month maturity bucket. In particular, the analysis of Chapter 3 assigns a prominent role to the MRO spread, i.e. the difference between the weighted average (r_w) and the marginal rate (r_m) of the ECB's main refinancing operations. Against this background, we investigate whether this auction-specific variable affects Euribor rates by inducing uncertainty in monetary policy expectations around the central path of future interest rates. For this purpose, we apply the following regression analysis:

$$\begin{aligned}\Delta IV(F_t) &= \sum\nolimits_{i=1}^{2} \lambda_i D_{t,i}(r_w - r_m)_t + \sum\nolimits_{i=1}^{3} \gamma_i D_{t,i}(\Delta OMO_t/OMO_{t-1}) \\ &+ \sum\nolimits_{i=1}^{3} \beta_{1,i} D_{t,i} \Delta itraxx_t + \sum\nolimits_{i=1}^{3} \beta_{2,i} D_{t,i}(KfW - bund)_t \\ &+ \delta' X_t + \upsilon_t, \qquad (4.3)\end{aligned}$$

where $IV(F_t(k))$ denotes the options' implied volatility of the 3M Euribor futures. To account for a potential increase of implied volatility due to elevated risk measures since August 2007, we include the risk variables of the previous section in our analysis. The results are presented in Table 18.

Our results obtained for the options implied volatility of 3M Euribor futures reveal various important insights. First, risk measures contribute to higher implied volatility. According to our estimates of $\beta_{1,2}$ and $\beta_{2,2}$, a daily change of the credit risk by 10 percentage points will increase uncertainty by roughly 1 percentage point. A change of the liquidity risk by the same order of magnitude increases the uncertainty by about 1.5 basis points. Second, large MRO spreads $(r_w - r_m)$ induce higher uncertainty ($\hat{\lambda}_2 > 0$) which in turn leads to significant and presumably policy-unintended increases of the longer-term money market rates. In fact, the implied volatility adjusts by 77.8% to changes in the MRO spread. That is, af-

Table 18: Uncertainty in Monetary Policy Expectations

Dependent Variable: $\Delta IV(F_t)$					
MRO Spread			*OMOs (outstanding volumes)*		
λ_1	Jun 2004 - Aug 2007	0.090 (1.25)	γ_1	Jun 2004 - Aug 2007	−0.007 (0.52)
λ_2	Aug 2007 - Oct 2008	0.778*** (2.75)	γ_2	Aug 2007 - Oct 2008	−0.609*** (6.15)
			γ_3	Oct 2008 - Dec 2009	−1.088*** (3.82)
Credit Risk			*Liquidity Risk*		
$\beta_{1,1}$	Jun 2004 - Aug 2007	0.055 (0.50)	$\beta_{2,1}$	Jun 2004 - Aug 2007	0.057 (0.41)
$\beta_{1,2}$	Aug 2007 - Oct 2008	0.116*** (2.65)	$\beta_{2,2}$	Aug 2007 - Oct 2008	0.145*** (3.12)
$\beta_{1,3}$	Oct 2008 - Dec 2009	0.131*** (3.18)	$\beta_{2,3}$	Oct 2008 - Dec 2009	0.155*** (2.63)
Calendar Dummies			*Intercept and Crisis Dummies*		
δ_{eoq}	End of Quarter	0.067*** (3.28)	δ_{cons}	Jun 2004 - Aug 2007	0.017 (0.32)
δ_{eos}	End of Semester	0.001 (0.23)	δ_1	Aug 2007 - Oct 2008	0.053** (2.09)
δ_{eoy}	End of Year	0.016 (0.65)	δ_2	Oct 2008 - Dec 2009	−0.204*** (3.02)
R^2		0.88	Obs.		1447
Wald test on parameter equality $\mathcal{H}_0 : \mathcal{D} = 0$					
$\mathcal{D}$:		p-value	$\mathcal{D}$:		p-value
$\lambda_1 - \lambda_2$		0.000			
$\gamma_2 - \gamma_3$		0.058	$\gamma_1 - \gamma_2$		0.000
$\beta_{1,1} - \beta_{1,2}$		0.008	$\beta_{2,1} - \beta_{2,2}$		0.000
$\beta_{1,2} - \beta_{1,3}$		0.634	$\beta_{2,2} - \beta_{2,3}$		0.651

Notes: Estimation of basis of daily data. HAC consistent, absolute t-statistics in parenthesis. ***,**,* indicate significance at the 1%, 5%, 10% level. The estimation model is presented in Equation (4.3). ***,**,* indicate significance at the 1%, 5%, 10% level. Wald statistics are presented as p-values.

ter August 2007 the outcome of MRO auctions generated uncertainty which then might have led to significant and presumably policy-unintended increases of the longer-term money market rates. And third, our results suggest that the net liquidity increase significantly reduced uncertainty after mid 2007. Ceteris paribus, the uncertainty seems to have been lower on average by roughly 20 percentage points ($\hat{\delta}_2$) after October 2008.

These results have several implications: first, the introduction of the fixed rate full allotment policy by the ECB as of October 2008 stopped the disturbing impact of the MRO spread on the uncertainty and thereby on longer-term money market rates. Second, the unconventional increase of liquidity supply helped also to reduce the uncertainty around the central path of future interest rates.

4.7 Conclusion

The ECB implements its monetary policy by steering the very short-term money market rate, i. e. the Eonia. In normal times, it is thereby able to influence the term money market rate, i.e. Euribor, which in turn determines short-term interest rates for retail bank loan and deposit rates. Since the outbreak of the financial crisis in August 2007, however, euro money market rates have been severely impaired causing Euribor rates to rise to unprecedented levels. In this paper, we have analyzed whether these developments have compromised the effectiveness of monetary policy in steering money market rates. Towards this aim, we have looked at two criteria. First, how well have monetary policy expectations been reflected in the money market yield curve and second, how has the ECB's crisis related (unconventional) monetary policy measures affected money market rates of three-month, six-month and twelve-month maturity.

Our results show that during the financial crisis the Euribor rates significantly deviate from the central path expected by market participants for monetary policy in the euro area. For the period from August 2007 through October 2008, we find that the dispersion of market expectations around its central scenario has increased and thereby significantly contributed to higher Euribor rates. The increased uncertainty can be attributed to (i) elevated risk measures and to (ii) the ECB's main refinancing operations: the difference between the prevailing weighted average and the marginal MRO rate. Additionally, our results indicate that from August 2007 through October 2008 longer-term money market rates have been heavily impacted by risk concerns, predominantly by liquidity premia.

For the period after October 2008, higher Euribor rates seem to be due to both liquidity and credit risk measures. Our results suggest that uncertainty in market expectations plays no significant role. Yet, our results reveal significant 'long memory' in Euribor rates. Compared to the period before mid 2007, we observe a fourfold, sixfold, and tenfold increase in the persistence of the three-month, six-month, and twelve-month Euribor rates, respectively. This finding suggests that potential shocks may last longer in Euribor rates and thereby severely impede their controllability.

These findings point to the weakened ability of the central bank to steer money market rates via standard monetary transmission channels. At the same time, however, we provide strong evidence that the ECB's crisis-related (non-standard) monetary policy measures have proven to be effective in reducing money market rates. Before the crisis, monetary policy operations were neutral with respect to the monetary policy stance, i.e. they did not affect money market rates at longer-term maturities directly. During the financial crisis, however, the significant expansion of the central bank balance sheet and the conduct of fixed rate tenders with full allotment have exerted a significant influence on the dynamics of money market rates at three-month, six-month, and twelve-month maturities. In particular, our results indicate that the ECB's net increase in outstanding open market operations as of October 2008 accounts for at least a 60 basis point decline in Euribor rates. We conclude that part of the loss in the effectiveness of monetary policy during the financial crisis via the traditional interest rate channel was compensated by the effective use of liquidity operations affecting money market rates beyond the daily maturity. Therefore, our results clearly show that central banks indeed have adequate tools at their disposal to conduct effective monetary policy, also in times of crises.

4.8 Appendix to Chapter 3

4.8.1 Testing the Expectations Hypothesis

The aim of this annex is to test the theoretical one-to-one relationship between euro area longer-term interest rates and the average expected overnight rate. For this purpose we will estimate the following representation for the complete sample from 16 June 2004 through 31 December 2009:

$$R_t(k) \quad = \quad c + \alpha \left(\frac{1}{k} \sum\nolimits_{j=0}^{k-1} E_t(r_{t+j}) \right) \tag{4.4}$$

where as in Equation (4.1) R denotes the Euribor rate of duration k. Similarly, we measure $\frac{1}{k} \sum_{j=0}^{k-1} E_t(r_{t+j})$ by $OIS_t(k)$. The results for the 3M, 6M, and 12M Euribor rates are presented in Table 19. The estimations of α provide empiri-

Table 19: Testing the Expectations Hypothesis

Dependent Variable: $R_t(k)$			
	$k = 3M$	$k = 6M$	$k = 12M$
c	0.292*** (13.89)	0.493*** (19.92)	0.576*** (19.95)
α	1.012*** (142.44)	0.960*** (122.06)	0.943*** (107.00)
R^2	0.91	0.88	0.84
Obs.	1447	1447	1447

Notes: HAC consistent, absolute t-statistics in parenthesis. ***,**,* indicate significance at the 1%, 5%, 10% level.

cal evidence for a one-to-one relationship between the levels of the term money market rates and expected future overnight rates over the same horizon. Table 20 reveals that for all maturities both series are co-integrated of order one, i.e. there is a long-term equilibrium relationship between longer-term interest rates and monetary policy expectations. Hence, our results do not suffer from a spurious regression problem.

Table 20: Johansen's Cointegration Test

Data trend	none	none	linear	linear	quadratic
Test type	no intercept no trend	intercept no trend	intercept no trend	intercept trend	intercept trend
trace(max-eig)					
$k = 3M$	1(1)	1(1)	1(1)	1(1)	1(1)
$k = 6M$	1(1)	1(1)	1(1)	1(1)	1(1)
$k = 12M$	1(1)	1(1)	1(1)	1(1)	1(1)

Notes: Selected number of cointegrating relations at the 5% level with a lag interval from 1 to 4.

4.8.2 Unit Root Tests

This section performs unit root tests on the Euribor and OIS rates for which the Augmented Dickey-Fuller *t*-statistics are presented in Table 21. For both the pre-crisis and crisis period, the Euribor and OIS rates of all considered maturities have a unit root, i. e. are I(1), and should thus be treated as non-stationary variables. To avoid the issues associated with non-stationarity, the Euribor and OIS rates should be expressed in first differences.

Table 21: Unit Root Tests

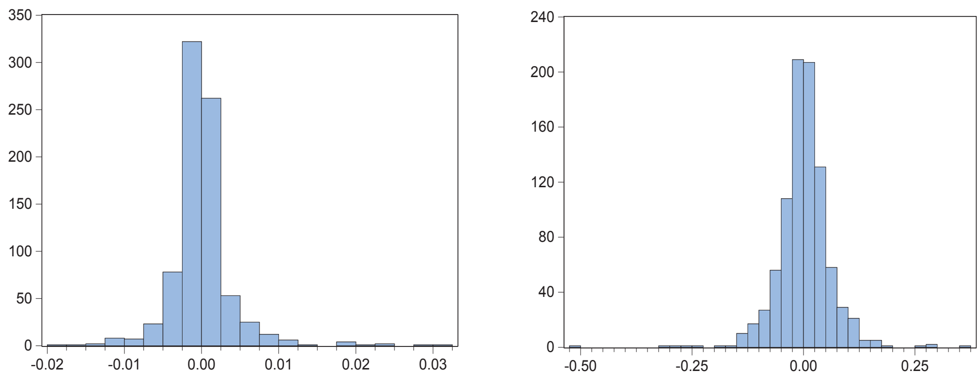
Variable	ADF Test		Variable	ADF Test	
	Pre-crisis	Crisis		Pre-crisis	Crisis
$R(3)$	-0.89	-1.24	$\Delta R(3)$	-24.34***	-5.89***
$R(6)$	-1.15	-0.98	$\Delta R(6)$	-26.59***	-7.35***
$R(12)$	-1.11	-0.74	$\Delta R(12)$	-28.33***	-8.63***
$OIS(3)$	-1.29	-1.23	$\Delta OIS(3)$	-30.76***	-6.87***
$OIS(6)$	-1.22	-0.90	$\Delta OIS(6)$	-31.58***	-19.56***
$OIS(12)$	-1.21	-0.94	$\Delta OIS(12)$	-29.02***	-21.50***

Notes: *** denote the significance at 1 % critical value. The t-statistic of the Augmented Dickey-Fuller (ADF) tests refer to the following test equation with a constant, a linear trend and the lag length according to the Schwarz Information Criterion. However, all results are robust against variation of the lag length or the deterministics in the equation.

4.8.3 iTraxx Market

Before the beginning of the financial turmoil, CDS premiums were not very volatile and were decreasing slowly but regularly. This continuous tightening of CDS premiums reflected both a relatively benign macroeconomic environment and improving profitability in most sectors. However, the fact that this trend became almost "mechanical", pushing CDS premiums to all-time lows, also probably reflected some complacency and underestimation of existing risks amongst market participants. Since July 2007, CDS spreads have dramatically increased and have been much more volatile, as a result of both the sharp credit deterioration (in particular in the financial sector) and of a significant re-pricing of credit risk.

Figure 14: Distribution of iTraxx Index Changes



(a) June 2004 - August 2007 (b) August 2007 - December 2010

Before July 2007, the distribution had a high positive skew (bigger number of observations in the right tail), and had a kurtosis much higher than 3: the positive skew might indicate that at the time, the CDS market reacted more strongly to negative credit news than to positive ones. Most large moves in CDS premia were CDS premiums widening, as a result of negative credit news. By contrast, a bigger number of observations corresponded to smaller decreases in CDS premiums. This behavior may appear as "normal", for a CDS is very similar to an insurance policy to protect oneself against risk, and usually insurance premia are

Table 22: Descriptive Statistics: iTraxx Index Changes

	June 2004 - Aug 2007	Aug 2007 - Dec 2010
mean	-0.0003	0.0015
median	-0.0003	0.0003
max	0.0303	0.3540
min	-0.0195	-0.5105
std	0.0040	0.0595
skewness	1.8669	-0.5386
kurtosis	16.3517	13.6801
Jarque-Bera	6487.02 [0.0000]	4296.93 [0.0000]

Notes: p-values are presented in parentheses.

more sensitive to bad news than good news. As for the fat tails of the distribution, they indicate that "extreme" changes in CDS premiums (as compared to the mean value) were more likely to happen, since the market was at the time very calm, with a low volatility (small standard deviation).

Since July 2007, the distribution has been much less skewed and less leptokurtic than it used to be. The skewness even became slightly negative (more observations in the left tail). The smaller skew might indicate that the CDS market responded almost in the same way both to credit deterioration and credit improvements, as there was no observed "mechanical" tightening or widening trend such as the one observed before the turmoil. It may also reflect the prevailing negative sentiment of the market: indeed, in pessimistic times, market dealers tend to re-price risk at higher levels on a regular basis, whereas in an optimistic environment, risk tends to be under-priced and CDS premia tend to decrease slowly. The observed slightly negative skew might also stem from sharp rises in risk pricing during the turmoil, followed by downturns in CDS premiums: in March 2008 for instance, the iTraxx index increased dramatically up to 160, and then decreased sharply to come back to its former levels. As for the smaller kurtosis, it might be due to the much higher standard deviation of the series: changes which used to be considered as "extreme" before the turmoil are now much more frequent.

4.8.4 Structural Break Test

This section uses structural break tests to investigate whether the period after August 9, 2007 significantly changed the dynamics of Euribor rates. To that aim, the Chow breakpoint test is applied to the equation of the Euribor, compare equation (4.2):

$$\begin{aligned}\Delta R_t(k) &= \sum\nolimits_{i=1}^{3} \alpha_{1,i} D_{t,i} \Delta OIS_t(k) + \sum\nolimits_{i=1}^{3} \alpha_{2,i} D_{t,i} \Delta IV(F_t) \\ &+ \sum\nolimits_{i=1}^{3} \beta_{1,i} D_{t,i} \Delta itraxx_t + \sum\nolimits_{i=1}^{3} \beta_{2,i} D_{t,i} (KfW - bund)_t \\ &+ \sum\nolimits_{i=1}^{3} \gamma_i D_{t,i} (\Delta OMO_t / OMO_{t-1}) + \gamma_4 D^{an}_{sLTRO\ 3M} \\ &+ \gamma_5 D^{an}_{sLTRO\ 6M} + \gamma_6 D^{an}_{sLTRO\ 12M} + \sum\nolimits_{i=1}^{3} \sum\nolimits_{j=1}^{5} \varphi_{i,j} D_{t,i} \Delta R_{t-j}(k) \\ &+ \delta' X_t + \epsilon_t \end{aligned} \tag{4.5}$$

We divide our sample from 16 June 2004 to 31 December 2009 into two subsamples and test whether there has been a break in all the equation parameters α, β, γ and φ_j as of August 9, 2007. The Chow breakpoint test compares the sum of

Table 23: Chow's Breakpoint Test

$\mathcal{H}_0$: No break at specified breakpoint			
Statistic	Euribor		
	$k = 3M$	$k = 6M$	$k = 12M$
F (08/09/2007)	14.90 (0.0000)	36.60 (0.0000)	78.89 (0.0000)
LR	183.61 (0.0000)	382.52 (0.0000)	714.04 (0.0000)
Wald	130.25 (0.0000)	268.97 (0.0000)	372.23 (0.0000)

Notes: Specified break date and p-values in parenthesis. Subsamples: March 10, 2004 to August 8, 2007 and August 9, 2007 to June 30, 2009 for the daily Euribor of three-month, six-month, and twelve-month horizon.

squared residuals obtained by fitting equation (4.5) to the entire sample with the sum of squared residuals obtained when separate equations are fit to each subsample. We report three test statistics for the Chow breakpoint test. The *F*-statistic is based on the comparison of the restricted and unrestricted sum of squared residuals. The *log likelihood ratio* statistic is based on the comparison of the restricted and unrestricted maximum of the (Gaussian) log likelihood function. The Wald statistic is computed from a standard Wald test of the restriction that the coefficients on the equation parameters are the same in all subsamples. While the *F*-statistic has an exact finite sample *F*-distribution, the *LR* and *Wald* test statistic have both an asymptotic χ^2 distribution with k degrees of freedom, where k is the number of parameters in the equation. The results confirm that the dynamics of Euribor rates have significantly changed since mid 2007. For all maturities, the test statistics strongly reject the null hypothesis of no structural change as of August 9, 2007.

Chapter 5

Interest Rate Dynamics and Monetary Policy Implementation in Switzerland

"In the real world, [...] it [credibility] is painstakingly built up by a history of matching deeds to words. A central bank that consistently does what it says will acquire credibility by this definition almost regardless of the institutional structure."
(Alan Blinder, 1998)

5.1 Introduction

The way monetary policy is implemented by the Swiss National Bank (SNB) differs from the procedures of most other central banks. Since the introduction of the SNB's new monetary policy framework in 1999, the maturity of the operational target of monetary policy has been a distinguishing feature of the SNB's operational framework. While other central banks use more or less explicit targets for the overnight rate to signal the policy-intended interest rate level, the SNB announces a target range for the three-month (three-month) Libor.[67] This paper investigates the working and the consequences of the SNB's unique operational framework for the behavior of Swiss money market rates before and during the financial crisis.

Following Jordan and Kugler (2004) and Swiss National Bank (2007), a major advantage of shifting the emphasis from the overnight rate to the three-month Libor is that it enables the SNB to react to financial shocks without having to declare a change in the stance of monetary policy. Therefore, overnight rate and three-month rate targeting might lead to similar outcomes in normal times, when large shocks are absent and spreads between interbank money market rates are low and stable. During the financial crisis, however, the behavior of Swiss interest rates suggests that the SNB's three-month rate targeting might have some additional features that could make it even interesting for other central banks.

The SNB manages the three-month Libor through both, words and deeds. First of all, the announced target rate itself should have an influence on the Libor. Moreover, since the current Libor will also depend on the expected path of the target range, the management of market expectations via e. g. interviews and speeches is of particular importance for the SNB, see e. g. Schlegel (2009). The SNB's communication of current and future target rates is substantiated by a very active liquidity management. The most important policy instruments are daily repo auctions with one-week maturity. The repo volume allotted in these auctions determines the level of reserves and, in addition, the pre-announced repo rate governs the one-week repo rate in the interbank money market. As a result, the repo rate can be seen as the SNB's intermediate policy rate to manage the three-month Libor.

In accordance with the central role of the 1W repo rate and the three-month Libor in the SNB's operational framework, our empirical analysis focuses on how these

[67] The London Interbank Offered Rate (Libor) is an *indicative* interest rate at which an individual contributor panel bank could borrow funds just prior to 12 a. m. CET. It serves as the main instrument for benchmarking short-term rates and is used as the basis for settlement of interest rate contracts on many of the world's major futures and options exchanges. For further details see www.bbalibor.com.

interest rates respond to various policy-relevant factors including e. g. deviations of the Libor from the target, changes in risk premia, market expectations, and the SNB's supply of reserves. In order to capture a possible change in interest rate dynamics and the SNB's monetary policy, both interest rate equations are estimated for the period before and after the outbreak of the financial crisis separately.

Our paper builds on earlier empirical contributions on the implementation of Swiss monetary policy. The reference closest to our work is Jordan and Kugler (2004) who also employ error-correction-type equations to explore the adjustment of Libor rates to deviations from the target. Jordan, Ranaldo and Söderlind (2009) propose a regime-dependent model to allow for a different response of the Libor before and during the financial crisis. Their findings confirm that repo operations and changes in the target rate are instrumental for the implementation of the SNB's monetary policy.

The structure of our paper is as follows. Section 5.2 provides a first look at the data and discusses several features of the SNB's operational framework. Section 5.3 presents the empirical results obtained for the adjustment equations of the repo rate and the three-month Libor before and during the financial crisis. In order to shed more light on the role of three-month rate targets for the control of three-month rates, we investigate how the ECB managed interest rates during the financial crisis. Section 5.4 gives a summary of our main results and concludes.

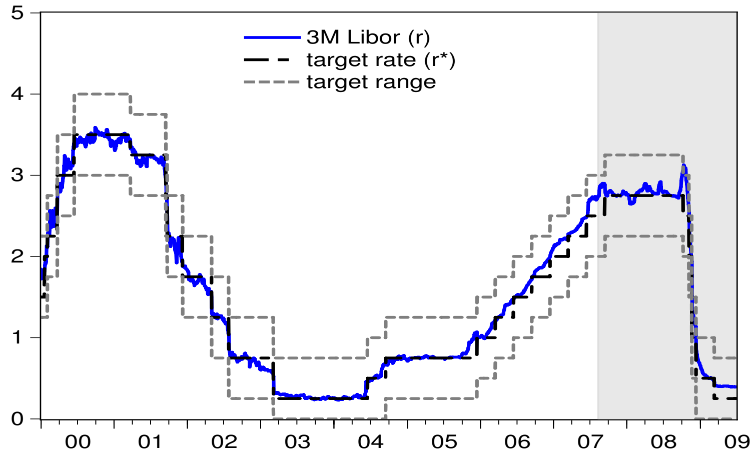
5.2 Three-Month Rate Targeting

In this section, we take a first look at the implementation of the SNB's three-month rate targeting. Section 5.2.1 describes how targets for the three-month rate are set and provides a preliminary assessment of their empirical performance. In Section 5.2.2 we discuss the specific role of interest rate expectations and the SNB's target corridor. Section 5.2.3 describes how the SNB uses regular open market operations to steer the three-month rate within the corridor. Section 2.4 compares the interest rate management of the SNB and the ECB during the financial crisis.

5.2.1 A First Look at the Data

On each Thursday in the third week of March, June, September and December, the SNB provides an assessment and addresses its decisions, concerns, views and outlook about monetary and economic developments. In particular, a target corridor of about 100 basis points is announced for the three-month Libor where the aimed level is typically determined by the middle of the corridor.[68] Target changes have always been communicated with an immediate effect.

Figure 15: Target Range of the SNB



Notes: The shaded area refers to the crisis period as of 9 August, 2007.

Figure 15 displays the three-month Libor (r), the target corridor and the target rate (r^*) for daily data from 3 January 2000 to 30 June 2009. Apparently, controllability of the three-month rate has not been a major problem for the SNB since the Libor followed its aimed level closely. Over the complete sample period, the average deviation of the Libor from the target rate is small, even during the financial crisis, see Table 24. The standard deviation indicates that there are also periods of marked deviations from the target. Yet, with only a few exceptions, the

[68] Exceptionally, the SNB deviated from this rule due to technical reasons. In 6 March, 2003, for instance, the SNB temporary narrowed down the target range from 100 to 75 basis points and intended to keep the three-month Libor rate at around 0.25%, i. e. at the lower end of the new target range.

Libor remained within the target corridor set by the SNB. These exceptions are all related to the unexpected and huge target changes in October and November 2008 in the aftermath of the Lehman breakdown.[69] Although both mean and standard deviation of the spread have increased, the preliminary data analysis already indicates that the SNB's three-month rate targeting even worked during the financial crisis.

Table 24: Libor Spread: Descriptive Statistics

	$r - r^*$				
Sample	Mean	Median	SD	Obs.	# Out
3 Jan 2000 – 8 Aug 2007	0.02	0.01	0.10	1982	0
9 Aug 2007 – 30 Jun 2009	0.10	0.06	0.14	495	12

Notes: r denotes the three-month Libor, r^* refers to the SNB's target rate. "# out" captures the number of days on which the three-month Libor is outside of the target range.

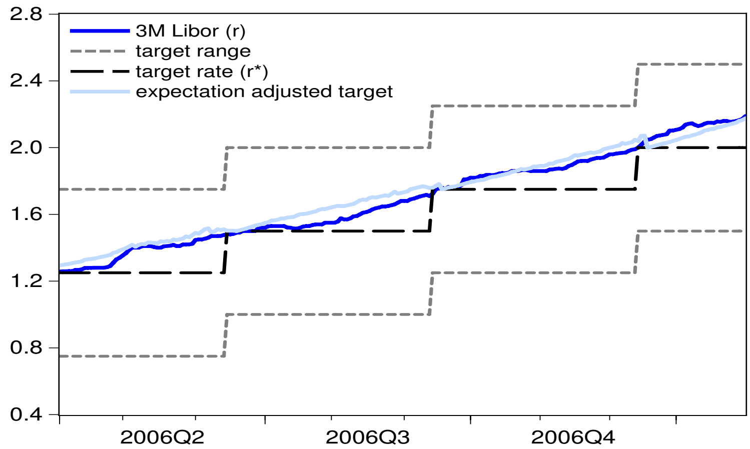
5.2.2 Rate Expectations and the Target Corridor

If policy is implemented via a target for a particular interest rate, large and persistent deviations of that rate from its target must be avoided, since those lead either to wrong signals about the intended rate or question the ability of the central bank to keep interest rates on track, see e. g. Hassler and Nautz (2008). Typically, central banks augment point targets for interest rates by a target corridor in order to deemphasize small and irrelevant deviations from the target. In case of overnight rate targeting, the corridor is often defined by the rates of standing facilities which bound the volatility of the overnight rate in a very simple and efficient way. In

[69] Starting on 8 October 2008, the three-month Libor crossed its upper bound for a period of roughly 10 days. With the unexpected 50-basis-point change on 6 November 2008, and the 100-basis-point change on 20 November 2008, the three-month Libor again exceeded the ceiling of its corridor each for a single day. This is (at least for the two latter cases) due to the timing of the Libor fixing, which has been prior to the decision announcements.

particular, with standing facilities the overnight rate will not leave its corridor simply due to arbitrage reasons. At first glance, the implementation of monetary policy via overnight rate and three-month rate targeting seem to be very similar since both approaches involve interest rate targets and corridors. However, if the emphasis of monetary policy is shifted from the overnight rate to a longer-term interest rate, this is not the whole story. For the SNB's operational framework, the role of rate expectations and the rationale of an interest rate corridor are different. Consider, for example, the deviations of the three-month Libor from the target in

Figure 16: Target Deviations in Times of Rate Change Expectations



Notes: The dashed black line represents the SNB's target rate for the three-month Libor, and the dotted grey lines represent the upper and lower bound of the target range, respectively. The solid black line refers to the three-month Libor while the solid grey line represents the target rate that has been adjusted for market participants' rate expectations implied by the three-month future rate.

2006 displayed in Figure 16. Obviously, these marked and persistent target deviations do not indicate bad communication or a failure of interest rate control. They are rather a direct consequence of the expectations hypothesis of the term structure that an anticipated and well-communicated change of the three-month rate target must lead to expectations-driven target deviations. In contrast to overnight rates, the three-month rate cannot simply stay at the old target level until the day of the rate change.[70]

This distinguishing feature of three-month rate targeting has two important implications. First, it provides a further rationale for the announcement and the width of a target corridor. Provided that target rate changes do not exceed 50 basis points, a corridor of 100 basis points guarantees that the three-month rate will be on target even immediately before an anticipated rate change. Second, in case of overnight rates, expected changes of the target rate can only be important several days before the implementation of the interest rate change. In contrast, as long as regular central bank meetings are scheduled at least every three months, rate expectations influence Swiss' three-month rates permanently, at each day between two meetings. Therefore, deviations of the three-month rate from the current target are not a feasible measure to evaluate the current interest rate level and the success of the targeting efforts by the central bank.

A more appropriate measure of the policy intended three-month rate, $\widetilde{r}_t^*$, is a convex combination of the current and the expected future target rate:

$$\widetilde{r}_t^* = r_t^* + w_t(f_t - r_t^*), \tag{5.1}$$

where f_t denotes the expected future target rate, and w_t represents a weighting factor. This weight increases (linearly) from zero to one as the expected subsequent target rate becomes more relevant over time. In the following, we use the interest rate on the (three-month) next future to proxy the expected future target rate. Using the future rate to calculate the implicit policy intended level of the three-month rate assumes that market expectations are generally in line with the plans of the SNB. Figure 16 shows the expectations-adjusted three-month rate target and the actual three-month rate for the time period from 2006 until the be-

[70]Many overnight-rate targeting central banks found it difficult to keep the overnight rate close to its target in times of rate change expectations. The ECB, for example, changed its operational framework in 2004 in order to stop the disturbing impact of rate change expectations on its liquidity management, see Hassler and Nautz (2008).

ginning of the financial crisis.[71] The small deviations between both interest rates reveal that three-month rate targeting worked particulary well in this period.

Shifting the focus of monetary policy from overnight rates to longer-term rates increases the role of rate expectations and, thus, the importance of the central bank's expectations management. The SNB governs market expectations on upcoming target changes in several ways, including speeches and interviews, see e. g. Schlegel (2009). Yet, the assumption of perfect anticipation of interest rate changes might be too strong. Following Jordan, Ranaldo and Söderlind (2009), we therefore include a measure of interest surprises into our empirical analysis. According to Hamilton (2009), daily three-month future rates capture daily changes in markets expectations of central banks near-term policy rate. Therefore, our surprise variable, $surpr$, is defined as the change in the three-month future on the day of SNB's regular monetary policy assessment meetings and zero otherwise.

5.2.3 The Repo Auctions of the SNB and the Repo Rate

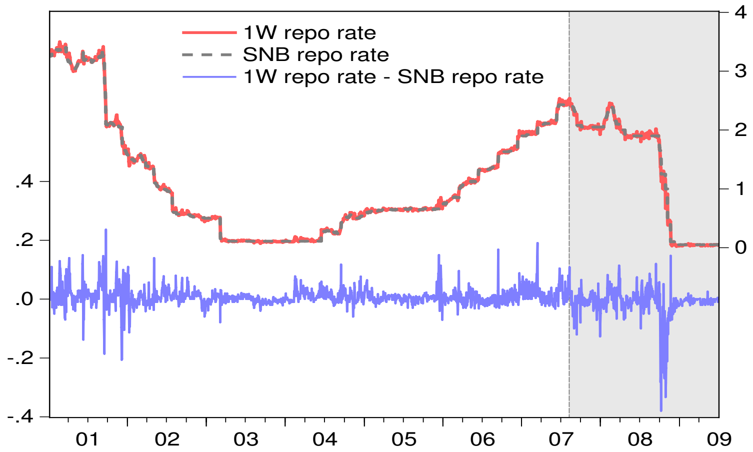
In addition to the management of interest rate expectations, repo auctions are the SNB's main instrument to steer the three-month Libor.[72] The results and refinancing conditions in these auctions determine the liquidity situation and, thus, the interest rates in the interbank money market. Probably reflecting both, the SNB's greater flexibility in the short-term money market (compare Baltensperger, Hildebrand and Jordan 2007) and the more ambitious operational target, the SNB is rather active in the money market. In the last years repo transactions with various maturities have been conducted on a daily basis. The most prevalent auction format are fixed rate tenders with a maturity of one week.[73] In a fixed rate tender, the SNB pre-announces the repo rate and banks simply bid the refinancing volume

[71] See appendix for the complete picture of the expectations-adjusted three-month rate target.

[72] See Kraenzlin and Schlegel (2009) for a comprehensive survey of the SNB's operational framework and an empirical analysis of banks' bidding behavior in repo auctions.

[73] From 2001 to 2003 one-week repo auctions were used in 27 % of the auctions, the SNB has used this maturity in approximately 90% of the cases ever since 2004, see Schlegel (2009).

Figure 17: SNB's Policy Instrument



Notes: The shaded area refers to the crisis period as of 9 August, 2007.

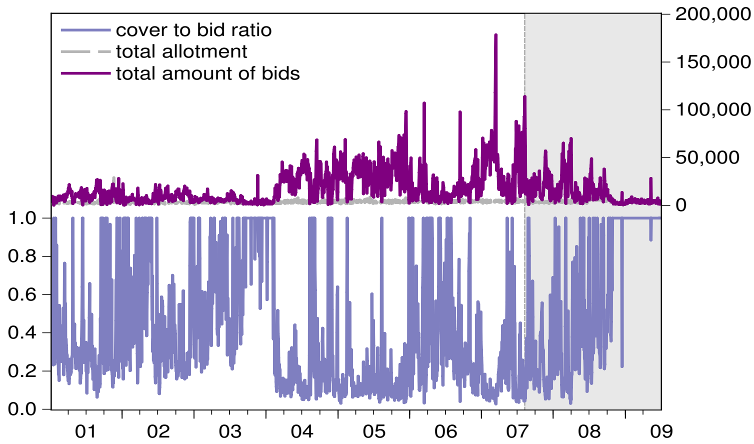
they like to achieve at that rate. Since banks' bidding behavior depend on the cost of alternative refinancing opportunities, the fixed repo rate set by the SNB has a direct influence on the one-week repo rate at the secondary market, see Figure 17. As a result, the one-week repo rate anchors the term structure of interest rates and can be seen as a starting point of the SNB's monetary transmission process. In the following empirical analysis of Swiss interest rate dynamics, we will use the repo rate rather than the auction rate as the SNB's policy rate because the secondary market rate $repo$ also reflects the impact of other monetary policy actions including the volume of allotted reserves or additional fine-tuning operations.[74]

The SNB's Supply of Reserves

If banks' total bids exceed the SNB's intended supply of reserves, the SNB rations all bids above a minimum amount proportionally. Following Jordan and Kugler (2004), our empirical analysis of the SNB's interest rate management considers the possible impact of the SNB's allotment decisions. Data on the SNB

[74]For instance, in the period after 6 October 2008, the widened spread between the one-week repo rate and the SNB's repo rate as depicted in Figure 17 reflects the impact of such additional measures.

Figure 18: Bids and Allotments in Repo Auctions



Notes: Right scale: the solid black line represents the total amount of bids submitted to the SNB's repo auctions by participating banks, whereas the dashed grey line refers to the total allotment of the SNB. Left scale: the solid grey line represents the cover to bid ratio, i.e. the ratio between total allotment and total bids.

refinancing auctions is available from 8 January 2001 onwards. The upper part of Figure 18 depicts the aggregate allotment volume and the total bid amount of all repo operations with one-week maturity.[75] Since 2004, the bid volumes have become larger because of the increased importance of one-week repo auctions in the set of the SNB's policy instruments. During the financial crisis, bids decreased because banks anticipated the full allotment policy of the SNB. In the lower part of the figure, we displayed the resulting cover to bid ratio, cbr, defined as the ratio of total allotment and total bids. Note that this ratio is far from constant and, typically, not easy to predict from the perspective of a single bank. In particular, there is no obvious upward trend in the cover-to-bid ratio. In contrast to the ECB, the SNB did not experience that banks started to increasingly exaggerate their bids in order to circumvent the rationing, see Nautz and Oechssler (2006). One explanation for the working of the SNB's fixed rate tender format is suggested by the time series of the spread between the fixed rate and the related market rate ($repo$), see

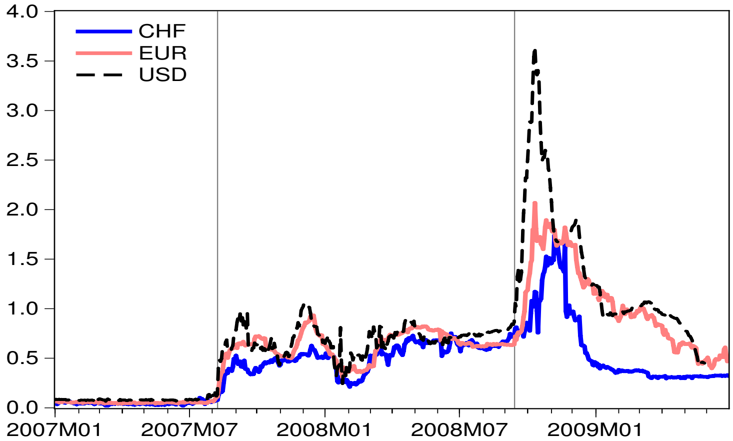
[75]On some few occasions, the SNB did not perform a one-week repo auction. In all these cases, we filled the data with the repo rate of the prevailing maturity. Following Jordan and Kugler (2004), there is no difference in the impact of repo auctions with different maturities.

Schlegel (2009). Figure 17 shows that the spread between both interest rates has been small but rather volatile and with changing sign. Therefore, overbidding in SNB's repo auctions might have been avoided because banks could not be sure to make profits by reselling excess reserves on the secondary market.

5.2.4 Interest Rate Targeting in the Financial Crisis: SNB and ECB

Since August 2007, the environment of an extreme nervousness among money market players started to have a great impact on global money markets. As a result, the concerns about liquidity, market and credit risk exposure - as reflected by the spread between the three-month Libor and the overnight index swap (OIS) rate - skyrocketed for major currencies, see Figure 19.

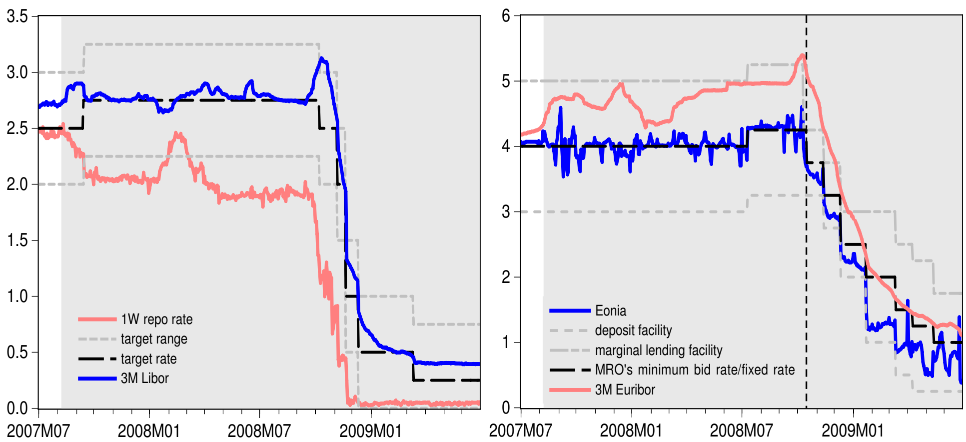
Figure 19: Risk Premia in the Financial Crisis



Notes: Following Taylor and Williams (2009), we define the risk premium as the spread between the Libor and the OIS rate. The first vertical line denotes the beginning of the crisis as of 9 August, 2007. The second vertical line represents the failure of Lehman on 15 September, 2008.

During the financial crisis, many central banks experienced unusual difficulties in implementing the policy-intended levels of short-term interest rates. For example, before the crisis the spread between the ECB's operational target, i.e. the overnight rate Eonia, and the policy rate, i.e. the minimum bid rate of the main refinancing operation, has been very small and to a large extent under the ECB's control.[76] In this calm period, risk premia were small and future short-term rates rather easy to predict. The spread between the three-month Euribor and the Eonia was under control and in line with policy intentions. This picture changed dramatically in the course of the financial crisis, see Figure 20.

Figure 20: Swiss and Euro Area Interest Rates in the Crisis



Notes: The vertical dashed line refers to 15 October 2008, when the ECB shifted its focus on longer-term interest rates by conducting longer-term repo auctions as fixed rate tenders with full allotment.

The massive liquidity injections of the ECB certainly helped to stabilize the banking sector but decoupled the Eonia from the minimum bid rate. Since the Lehman breakdown, banks have used the ECB's deposit facility on a large scale to deposit excess reserves. As a result, the deposit rate has become the new reference rate for the Eonia. Although the ECB did not officially announce a new interest rate targeting regime, there is certainly an increased concern about the level of longer-term money market rates. The observed change in the ECB's interest rate management might have led to some confusion of market participants about the policy intended interest rate level. Compared with the ECB, the changes in the SNB's operational framework stirred by the crisis have been relatively small. In

[76] Before the crisis, even target deviations of only a few basis points lead to discussions about the ECB's monetary setup, see e. g. Linzert and Schmidt (2011).

particular, the SNB did not abandon its operational target. Mean and volatility of the spread between the three-month Libor and its target have only slightly increased during the financial crisis, see Section 5.2.1. Figure 20 shows that the SNB decreased its repo rate dramatically in order to keep the three-month Libor close to its target. The transparency of the SNB's interest rate policy might have contributed to keep the risk premia revealed by the Libor-OIS spreads relatively low, see Figure 19.

5.3 Empirical Results

In accordance with the SNB's operational framework of monetary policy, the following empirical analysis focusses on the dynamics and adjustment processes of the one-week repo rate and the three-month Libor. For both interest rates, error-correction type equations are employed to estimate how the interest rates respond to various policy-relevant factors, see Jordan and Kugler (2004). Due to data availability, we use daily data ranging from 8 January 2001 until 30 June 2009. To control for the effects of the financial crisis on interest rate dynamics, both interest rate equations are estimated separately for the period before and after 9 August, 2007.

5.3.1 The Dynamics of the Policy Instrument

We begin with the estimation of the adjustment equation of the SNB's policy rate, i.e. the one-week repo rate (of the secondary money market), which is specified as follows:

$$\begin{aligned}\Delta repo_t &= \alpha(r - \widetilde{r}^*)_{t-1} + \beta(r - repo)_{t-1} + \sum_{j=1}^{5} \gamma_j \Delta risk_{t-j} + \sum_{j=0}^{5} \delta_j \Delta r^*_{t-j} \\ &+ \sum_{j=1}^{5} \varphi_j \Delta repo_{t-j} + \theta \ln cbr_t + \phi\, surpr_t + \mu + u_t. \qquad (5.2)\end{aligned}$$

Following Section 5.2, the one-week repo rate ($repo$) should respond to the ***Libor spread*** $(r - \widetilde{r}^*)$, i.e. to deviations of the three-month Libor (r) from the expectations adjusted target rate ($\widetilde{r}^*$), see Section 5.2.2. A second error-correction term is suggested by the expectations hypothesis of the term structure which implies that the ***term spread*** $(r - repo)$ is stationary even if the level of interest rates is non-stationary.[77] Non-stationary interest rates of different maturities are only co-integrated if risk premia are stationary. According to Section 5.2.4, stationarity of risk premia has become questionable during the financial crisis. While changes in the level of $risk$, measured as Libor-OIS spread, have been virtually negligible before the financial crisis, large swings of $risk$ could have affected the interest rate management of central banks since the onset of the turmoil. The adjustment equation of the one-week repo rate therefore controls for changes in the risk premium of the three-month Libor. In line with Jordan and Kugler (2004), the one-week repo rate may respond to the allotment decisions made in the SNB's repo auctions. Following Section 2.3, large cover-to-bid ratios (cbr) indicate a generous supply of liquidity which should lead to a decrease in the repo rate. Finally, we follow Jordan, Ranaldo and Söderlind (2009) and control for the effect of policy surprises ($surpr$) defined by the change of the future rate observed at the day of a policy meeting.

Table 25 summarizes the estimation results obtained for the adjustment equation of the one-week repo rate before and during the financial crisis.[78] The results suggest several conclusions regarding the SNB's implementation of monetary policy. First of all, the adjustment coefficient α is statistically significant and plausibly signed for both sample periods. As expected, the SNB adjusts the one-week repo rate in response to observed deviations of the three-month Libor from the target rate. In particular, if the Libor exceeds the expectations-adjusted target, the one-week repo rate is lowered to bring the three-month rate down. The response of

[77]In fact, while unit root tests indicate that both interest rates are integrated of order one, the term spread can be assumed to be stationary. For similar results for euro area and U.S. interest rates, see e. g. Nautz and Offermanns (2007) and Sarno and Thornton (2003).

[78]A complete presentation of the estimation results is shown in the Appendix.

the repo rate might have been even stronger since the financial crisis, probably indicating increased efforts of the SNB to keep the Libor close to its target.

Table 25: Adjustment Equation of the SNB's Policy Instrument

Variable	Coefficient	Sample	
		pre-crisis	crisis
Exp.-adj. Libor Spread	α	-0.035^{**} (1.97)	-0.050^{**} (2.13)
Term Spread	β	0.037^{**} (2.52)	-0.009 (1.09)
Monetary Policy Surprise	ϕ	0.355^{*} (1.66)	0.157 (0.97)
Change in Risk Premium	$\sum_{j=1}^{5} \gamma_j$	-0.571^{***} (3.86)	-0.478^{***} (2.47)
Cover to bid ratio	θ	-0.003^{***} (4.59)	-0.0001 (0.03)
R^2		0.26	0.22
Obs.		1718	494

Notes: The table refers to Equation (5.2):

$$\Delta repo_t = \alpha(r - \widetilde{r}^*)_{t-1} + \beta(r - repo)_{t-1} + \sum_{j=1}^{5} \gamma_j \Delta risk_{t-j} + \theta \ln cbr_t + \phi\ surpr_t + \ldots + u_t.$$

***, **, * indicate significance at the 1%, 5%, 10% level. Absolute t-statistics in parentheses are computed according to Newey and West (1987) . The pre-crisis sample runs from 3 January 2000 to 8 August 2007, the crisis sample ends in 30 June 2009. The full set of estimation results for this equation can be found in Table 28 in the appendix.

By contrast, the adjustment coefficient of the term spread (β) clearly differs before and during the financial crisis. Before the crisis, the estimated response of the repo rate to the term spread is in line with the predictions of the expectations theory of the term structure. During the crisis, however, the estimate of β is not significant and even implausibly signed. In the financial crisis, increases in the three-month Libor were certainly not due to expected future increases of the one-week repo rate but resulted from increases in risk premia. Therefore, the breakdown of the standard expectations-based equilibrium relation between the one-week repo rate and the three-month Libor reflects the SNB's active interest rate management via the one-week repo rate.

In both periods there is a significant reaction of the repo rate to changes in the risk premium. Interestingly, the long-run effect of changes in risk on the repo rate, $\sum_{j=1}^{5} \gamma_j$, is largely unaffected by the crisis. In both periods, increases in the risk premium were followed by a decreasing repo rate. Given the structural stability of the SNB's response to changes in risk, the large and persistent risk premia during the crisis explain a major part of the behavior of repo rates.

As expected, large cover-to-bid ratios indicate a generous liquidity supply and lead to decreasing repo rates in the pre-crisis sample. In the crisis, this plausible effect disappears because cover-to-bid ratios were typically one as a result of the full allotment policy of the SNB. Finally, we find minor significant impact of the surprise variable on the repo rate. This can be partly explained by the maturity mismatch between the one-week rate and the surprise measure which recurs to the three-month next future. However, it also shows that the one-week rate carries only little information about the monetary policy stance, and thus, is little affected by the SNB's longer-term assessments.

5.3.2 The Dynamics of the Operational Target

Let us now turn to the empirical analysis of the three-month Libor dynamics. Similar to Jordan and Kugler (2004) and the adjustment equation employed for the repo rate, the analysis of the three-month Libor dynamics is based on an error-correction-type adjustment equation:

$$\begin{aligned} \Delta r_t &= \alpha(r - \widetilde{r}^*)_{t-1} + \beta(r - repo)_{t-1} + \sum_{j=0}^{5} \delta_j \Delta r^*_{t-j} \\ &+ \sum_{j=1}^{5} \varphi_j \Delta repo_{t-j} + \sum_{j=1}^{5} \psi_j \Delta r_{t-j} + \phi\, surpr_t + \mu + v_t. \end{aligned} \tag{5.3}$$

The response of r_t to the error-correction terms reflects the two channels, words and deeds, of the SNB's interest rate management. First, a successful expectations management of the SNB should imply that the three-month Libor adjusts significantly to the expectation-adjusted target rate $\widetilde{r}^*_t$. Second, if the SNB can actually influence the three-month Libor via the repo rate, there should be a significant response of the three-month Libor to the repo rate via the term spread, $(r - repo)$.

The SNB announces the conditions of the repo auction at 9 a. m. CET on each operation day and invites banks to submit their bids. The auction is closed at 9.10 a. m. CET and individual results are being announced at (roughly) 9.20 a. m. CET including both the total bid and total allotment. The Libor fixing occurs at 12 a. m. CET.

Table 26: The Adjustment Equation for the three-month Libor

Variable	Coefficient	Sample	
		pre-crisis	crisis
Exp.-adj. Libor Spread	α	-0.040^{**} (2.41)	-0.026^{***} (3.59)
Term Spread	β	-0.003 (0.38)	-0.007^{***} (3.42)
Monetary Policy Surprise	ϕ	0.390^{**} (2.00)	0.282^{***} (2.79)
Persistence	$\sum_{j=1}^{5} \psi_j$	0.165^{**} (2.04)	0.613^{***} (10.33)
R^2		0.26	0.87
Obs.		1723	494

Notes: The table refers to Equation (5.3):

$$\Delta r_t = \alpha(r - \widetilde{r}^*)_{t-1} + \beta(r - repo)_{t-1} + \sum_{j=1}^{5} \psi_j \Delta r_{t-j} + \phi\ surpr_t + \ldots + v_t.$$

The full set of estimation results for this equation can be found in Table 29 in the Appendix. Note that the R^2 in the crisis period is inflated by dummy variables capturing two outliers in November and December 2008. For further notes, see Table 25.

Table 26 summarizes the results obtained for the adjustment equation of the three-month Libor before and during the crisis. For both periods, the significant and plausibly signed error-correction coefficient α related to the expectations-adjusted target rate clearly indicates the existence of the "words channel" of monetary policy implementation. Remarkably, the size of the coefficient is almost the same in both periods. The channel of steering the three-month rate by signals about the current and future level of the target rate seems to be unaffected by the financial crisis. Focusing on the dynamics of the adjustment equation for the three-month Libor, the half-life period of a shock to the expectations-adjusted target rate $\widetilde{r}^*$ is about 19 days before and 23 days during the crisis.

The adjustment coefficient β of the three-month Libor to the term spread is significantly negative in the crisis period and insignificant before. This suggests that the role of the one-week repo rate and, thus, of the 'deeds channel' of monetary policy implementation has increased in the crisis period. Note that the significant adjustment of the three-month Libor to the repo rate cannot be explained by simple expectations effects. In fact, a typical finding of the empirical literature on interest rate dynamics is that longer-term interest rates are weakly exogenous and do not adjust to interest rates with shorter maturities, see e. g. Sarno and Thornton (2003) and Hassler and Wolters (2001).

Our empirical results suggest that the working of the SNB's interest rate management in the financial crisis can be illustrated as follows. Suppose that an increase in the risk premium ($\Delta risk > 0$) had caused an unwished increase in the three-month Libor above its expectations-adjusted target, i.e. $r - \widetilde{r}^* > 0$. According to Table 25, the SNB responds to the equilibrium deviation with a decrease in the one-week repo rate which in turn will increase the term spread $r - repo$. Finally, Table 26 shows how the increased term spread helps to bring the three-month Libor back to target.

Two further results shown in Table 26 are worth noting. First, there has been a significant increase in the persistence of the three-month Libor during the crisis. Second, while the surprise variable played no role for the dynamics of the repo rate, our estimates show that monetary policy surprises have a significant impact on the three-month rate. This confirms the different functions of the two interest rates: it is the three-month rate through which the SNB's monetary policy stance is transmitted, and not the one-week rate.

5.3.3 Interest Rate Management of the ECB

In order to shed more light on the SNB's approach of monetary policy implementation, let us now compare the Swiss interest rate dynamics during the financial crisis with those recently observed in the euro area. In the course of the financial crisis, the ECB shifted the attention increasingly to the management of longer-term money market rates, like the three-month Euribor. In the following, we therefore investigate to what extent the ECB's monetary policy implementation has become equivalent to the three-month rate targeting approach of the SNB.

Since the beginning of the financial crisis in August 2007, the interest rate management of the ECB can be divided into two regimes. In the first year of the crisis, until the Lehman breakdown in September 2008, the ECB still tried to keep the Eonia close to its key policy rate, i.e. the minimum bid rate of its main refinancing operation (MRO). However, the ECB also began to be explicitly concerned about stabilizing longer-term money market rates. To that aim, the ECB increased drastically the volume and frequency of its longer-term refinancing operations (LTROs). While the share of LTROs in total refinancing was 33% in the first half of 2007, it rose to more than 60% in the beginning of 2008, see European Central Bank (2009, p. 79). All these LTROs had been conducted as variable rate tenders. In contrast to MROs, however, the LTROs were performed without a minimum bid rate. Therefore, the ECB sent no signal about the intended longer-term repo rate and thus, its impact on Euribor rates has been limited.

Banks became more and more reluctant to lend to each other and the distribution of liquidity was severely impaired. Even solvent banks were observed to experience problems with refinancing through the interbank money market. As a result, banks increased their recourse to the ECB's refinancing operations and the average MRO interest rate jumped to more than 70 basis points above the minimum bid rate. Moreover, Libor-OIS spreads revealed that particularly the three-month Euribor was inflated by a huge risk premium. In view of these extreme disturbances, the ECB partly abandoned the overnight rate Eonia as its operational target (see Section 2.4) and adjusted its operational framework in several ways, see European Central Bank (2009). In particular, the ECB switched from the variable rate to the fixed-rate tender format with full allotment in all refinancing operations. Moreover, the repo rate set by the ECB was the same for all maturities. Therefore, from 15 October 2008 onwards, by announcing a fixed rate for liquidity provision in the three-month horizon, the ECB basically published a target for the three-month Euribor.

Table 27 shows the estimated adjustment equation of the three-month Euribor obtained for the crisis period. For sake of comparison, the specification follows the equation employed for the three-month Libor in the previous section. In particular, we used the minimum bid rate (MBR) as the ECB's policy instrument and the marginal LTRO rate as implicit target for the three-month rate.

Table 27: Adjustment of the three-month Euribor in the Crisis

Variable	Coefficient	
Euribor Spread in variable rate tender period	α^{var}	0.002 (0.52)
Term Spread in variable rate tender period	β^{var}	−0.002 (0.82)
Euribor Spread in fixed rate tender period	α^{fix}	−0.012*** (3.18)
R^2		0.64
Obs.		487

Notes: The table summarizes the main estimation results of the adjustment equation for the three-month Euribor in the crisis period:

$$\Delta r_t = \alpha^{var}(r - \widetilde{r}^*)_{t-1} \cdot (1 - D_t^{fix}) + \beta^{var}(r - repo)_{t-1} \cdot (1 - D_t^{fix})$$

$$+ \ \alpha^{fix}(r - \widetilde{r}^*)_{t-1} \cdot D_t^{fix} + \ldots + v_t,$$

where D_t^{fix} equals one in the fixed-rate tender period from 15 October 2008 to 30 June 2009, and zero otherwise. Note that the term spread in the fixed rate tender regime is identical to the Euribor spread during that period. The full set of estimation results for this equation can be found in Table 30 in the Appendix. For further notes, see Table 25.

To take into account the ECB's switch from variable to fixed rate tenders, we use an indicator variable that equals one during the fixed-rate tender regime starting in 15 October 2008, and zero before. The insignificant adjustment coefficients of both error-correction terms show that the ECB's impact on the three-month Euribor has been weak in the variable-rate tender regime. By contrast, the adjustment coefficient of the fixed rate regime is highly significant and plausibly signed. In contrast to the SNB, the ECB not only sends signals about the policy-intended level of the three-month Euribor. Rather, using fixed-rate tenders with full allotment, the ECB directly intervenes in the three-month money market segment. Apparently, the introduction of fixed rate tenders together with the commitment of full allotment at the target rate significantly improved the ECB's control over longer-term money market rates.

5.4 Conclusion

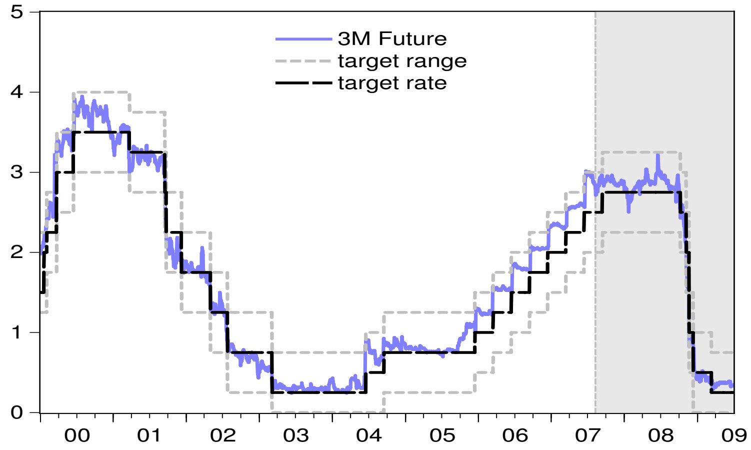
Over the last ten years, a distinguishing feature of the SNB's monetary policy framework has been the announcement of a target corridor for the three-month Libor. This paper investigated the empirical relevance of this target for the interest rate dynamics of the three-month Libor and one-week repo rate, i.e. the SNB's main policy rate. Our empirical results show that the SNB controls the three-month Libor through both, words and deeds. On the one hand, we find a significant response of the three-month Libor to deviations from its expectations-adjusted target rate. On the other hand, the repo rate had been actively used to counteract increases in the Libor caused by risk premia.

While standard overnight rate and three-month rate targeting should lead to similar results in normal times, the financial crisis showed that the SNB's approach to monetary policy implementation might have some additional features. In particular, the transparency of the SNB's interest rate policy during the crisis seems to have contributed to keep the risk premia revealed by the Libor-OIS spreads relatively low.

5.5 Appendix to Chapter 4

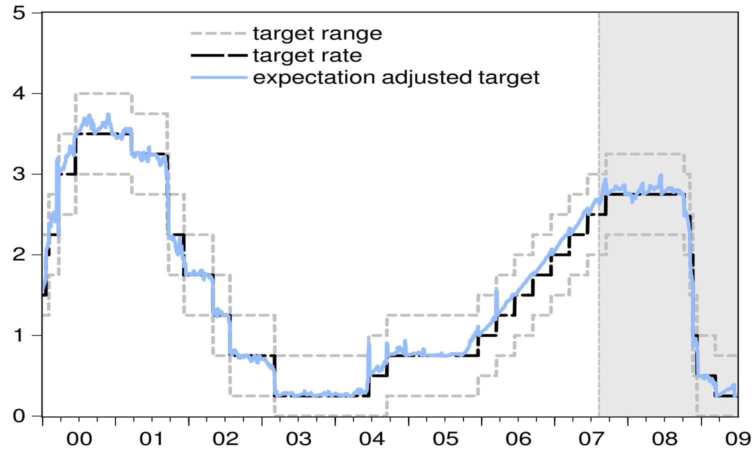
5.5.1 Figures

Figure 21: Three-month Next Future Rate



Notes: The solid black line refers to the three-month future rate. The dotted grey lines represent the target range for the three-month Libor. The dashed black line denote the SNB's target rate. The shaded area refers to the crisis period as of 9 August, 2007.

Figure 22: Expectation Adjusted Target



Notes: The solid black line refers to the target rate that has been adjusted for market participants' rate expectations implied by the three-month future rate. The dotted grey lines represent the target range for the three-month Libor. The dashed black line denote the SNB's target rate. The shaded area refers to the crisis period as of 9 August, 2007.

5.5.2 Tables

One-week Repo Rate Dynamics

$$\Delta repo_t = \alpha(r-\widetilde{r}^*)_{t-1} + \beta(r-repo)_{t-1} + \sum_{j=1}^{5}\gamma_j \Delta risk_{t-j} + \sum_{j=0}^{5}\delta_j \Delta r^*_{t-j} + \sum_{j=1}^{5}\varphi_j \Delta repo_{t-j} + \theta \ln cbr_t + \phi\, surpr_t + \mu + u_t.$$

Table 28: Adjustment Equation of the SNB's Policy Instrument

Variable	Coefficient	Sample	
		pre-crisis	crisis
Exp.-adj. Libor Spread	α	-0.035^{**} (1.97)	-0.050^{**} (2.13)
Term Spread	β	0.037^{**} (2.52)	-0.009 (1.09)
Change in Risk Premium	γ_1	-0.277^{***} (5.34)	-0.096 (0.83)
	γ_2	-0.126^{***} (2.78)	-0.106 (1.33)
	γ_3	-0.122^{***} (2.97)	-0.065 (0.79)
	γ_4	-0.019 (0.43)	-0.173^{*} (1.95)
	γ_5	-0.027 (0.49)	-0.038 (0.84)
Change in Target Rate	δ_0	0.157^{***} (3.17)	-0.040 (0.78)
	δ_1	0.246^{***} (4.49)	0.184^{*} (1.87)
	δ_2	0.122^{***} (3.14)	0.185^{**} (2.05)
	δ_3	0.053^{*} (1.65)	0.051 (1.05)
	δ_4	0.106^{***} (2.69)	0.026 (0.42)
	δ_5	0.106^{***} (2.97)	0.103 (1.40)
Persistence	φ_1	-0.078 (1.42)	-0.025^{***} (3.17)
	φ_2	-0.065 (1.20)	-0.020^{***} (2.62)
	φ_3	-0.020 (0.61)	-0.179 (1.20)
	φ_4	-0.126^{***} (3.21)	-0.124 (1.41)
	φ_5	0.029 (0.65)	0.090 (1.17)
Cover to bid ratio	θ	-0.003^{***} (4.59)	-0.0001 (0.03)
Monetary Policy Surprise	ϕ	0.355^{*} (1.66)	0.157 (0.97)
Constant	μ	-0.011^{***} (3.93)	0.005 (0.80)
R^2		0.26	0.22
Obs.		1718	494

Notes: Estimated coefficients of Equation (5.2). ***,**,* indicate significance at the 1%, 5%, 10% level. Absolute t-statistics are computed according to Newey and West (1987). The pre-crisis sample runs from 3 January 2000 to 8 August 2007, and the crisis sample ends in 30 June 2009.

Three-Month Libor Dynamics

$$\begin{aligned}\Delta r_t &= \alpha(r-\widetilde{r}^*)_{t-1}+\beta(r-repo)_{t-1}\\ &+ \sum_{j=0}^{5}\delta_j\Delta r^*_{t-j}+\sum_{j=1}^{5}\varphi_j\Delta repo_{t-j}+\sum_{j=1}^{5}\psi_j\Delta r_{t-j}+\phi\; surpr_t+\mu+v_t.\end{aligned}$$

Table 29: Adjustment Equation of the three-month Libor

Variable	Coefficient	Sample	
		pre-crisis	crisis
Exp.-adj. Libor Spread	α	-0.040^{**} (2.41)	-0.026^{***} (3.59)
Term Spread	β	-0.003 (0.38)	-0.007^{***} (3.42)
Change in Target Rate	δ_0	0.081^{*} (1.89)	-0.001 (0.17)
	δ_1	0.168^{***} (2.80)	0.191 (1.35)
	δ_2	-0.042^{**} (2.01)	-0.052^{**} (2.18)
	δ_3	-0.021 (1.17)	-0.024^{*} (1.93)
	δ_4	0.015 (0.61)	-0.032^{**} (2.03)
	δ_5	-0.008 (0.55)	-0.027^{**} (2.44)
Change in Repo Rate	φ_1	0.026 (1.05)	-0.071^{***} (2.75)
	φ_2	0.022 (0.73)	-0.021 (1.05)
	φ_3	0.010 (0.40)	-0.068^{***} (3.59)
	φ_4	0.038^{***} (1.51)	-0.028 (1.17)
	φ_5	0.043^{**} (2.00)	-0.016 (1.23)
Monetary Policy Surprise	ϕ	0.390^{**} (2.00)	0.282^{***} (2.79)
Persistence	ψ_1	0.116^{**} (2.41)	0.352^{***} (7.82)
	ψ_2	0.034 (0.87)	0.076^{***} (2.92)
	ψ_3	0.016 (0.41)	0.080^{***} (4.02)
	ψ_4	-0.016 (0.40)	0.074^{***} (3.51)
	ψ_5	0.014 (0.40)	0.031^{*} (1.82)
Constant	μ	-0.002 (0.98)	0.005^{***} (3.72)
R^2		0.26	0.87
Obs.		1723	494

Notes: Estimated coefficients of Equation (5.3). Note that the R^2 in the crisis period is inflated by dummy variables capturing two outliers in November and December 2008. For further notes, see Table 28.

Three-Month Euribor Dynamics

$$\begin{aligned}\Delta r_t &= \alpha^{var}(r-\widetilde{r}^*)_{t-1}\cdot(1-D_t^{fix})+\alpha^{fix}(r-\widetilde{r}^*)_{t-1}\cdot D_t^{fix}\\&+\beta^{var}(r-repo)_{t-1}\cdot(1-D_t^{fix})\\&+\sum_{j=0}^{5}\delta_j\Delta r^*_{t-j}+\sum_{j=0}^{5}\varphi_j\Delta repo_{t-j}+\sum_{j=1}^{5}\psi_j\Delta r_{t-j}+\mu+v_t.\end{aligned}$$

Table 30: Adjustment Equation of the three-month Euribor in the Crisis

Variable	Coefficient	
Euribor Spread in variable rate tender period	α^{var}	0.002 (0.52)
Term Spread in variable rate tender period	β^{var}	−0.002 (0.82)
Euribor Spread in fixed rate tender period	α^{fix}	−0.012*** (3.18)
Change in Target Rate	δ_0	0.014 (1.00)
	δ_1	−0.013* (1.67)
	δ_2	−0.002 (0.49)
	δ_3	−0.006 (1.31)
	δ_4	−0.002 (0.23)
	δ_5	−0.009 (1.44)
Change in Repo Rate	φ_0	0.008 (0.29)
	φ_1	0.116*** (5.91)
	φ_2	0.001 (0.04)
	φ_3	0.019 (1.19)
	φ_4	0.022 (1.41)
	φ_5	−0.047** (2.30)
Persistence	ψ_1	0.521*** (6.92)
	ψ_2	0.036 (0.51)
	ψ_3	0.104** (1.98)
	ψ_4	0.082 (1.28)
	ψ_5	0.006 (0.13)
Constant	μ	0.001 (0.59)
R^2		0.64
Obs.		487

Notes: Estimated coefficients of an equation analogously to (5.3) for the three-month Euribor. Note that the term spread in the fixed rate tender regime is identical to the Euribor spread during that period. For further notes, see Table 28.

Chapter 6

Conclusion

The economic history has shown that crises are often associated with substantial changes in the monetary policy paradigm. During the Great Depression of the 1930s, for instance, central bankers were held responsible for worsening the economic downturn, see e. g. Goodfriend (2007). This caused monetary policy to be placed under the control of fiscal authorities. The failure of monetary policy to stabilize inflation during the Great Inflation Era of the 1970s led to the establishment of a monetary policy framework safeguarded by independent and autonomous central bankers whose primary mandate relied on price stability. The Great Financial Crisis that started in 2007 has exposed the limitations of conventional channels through which monetary policy operates, see Bean et al. (2011) and Stark (2011). In order to assess the implications of this crisis for the post-crisis monetary policy framework, many aspects of the pre-crisis paradigm need to be carefully re-examined. On the basis of the recent experience, this thesis investigates some of the core aspects of the existing operational framework and evaluates the monetary policy responses to the crisis, using primarily the example of the European Central Bank (ECB) and of the Swiss National Bank (SNB).

The second chapter reveals a mutual interrelation between money market tensions and the stability of the broader financial system that central banks need to take into account when accommodating shocks to banks' liquidity demand. In line with recent theoretical contributions, the analysis finds that an asymmetric distribution of liquidity in the banking sector, a larger dispersion of credit risk in the interbank market, more volatile asset prices, a higher maturity mismatch, and a larger fraction of banks persistently refinancing though central bank operations increase the demand for central bank money. In the third chapter, the relation between the ECB's main refinancing (MRO) rates and the money market is investigated, i.e. the first step of the monetary transmission process in the euro area. The results confirm a stabilizing level relationship between the overnight rate Eonia and MRO rates before the financial crisis. Since the start of the financial crisis, however, the findings suggest that MRO auction outcomes even exacerbated the disconnection of money market rates from the policy-intended interest rate level. Against the background of elevated longer-term money market rates throughout the financial crisis, the fourth chapter studies the effectiveness of monetary policy in steering euro area money market rates during the crisis. The study relies on two measures: first, the predictability of money market rates on the basis of monetary policy expectations, and second the impact of extraordinary central bank measures on money market rates. The analysis shows that interest rates of money market loans until the twelve-month maturity segment deviate significantly from the central path of monetary policy expectations after August 2007 compared to the pre-crisis period. Additionally, the results indicate that the uncertainty around this central path has contributed to elevated term money market rates. At the same time, the analysis implies that the ECB's net increase in outstanding open market operations as of October 2008 accounts for a decline in Euribor rates by more than 60 basis points. The fifth chapter of this thesis reviews the operational framework of a central bank that announces a range for the three-month term money market interest rate as its operational target. This chapter explores the working and the consequences of the SNB's unique operational framework for the behavior of Swiss term money market rates before and during the financial crisis.

The results of this thesis provide important implications for the future conduct of monetary policy in 'new normal' times. First, we challenge the liquidity-neutral allotment policy of the ECB conducted until October 2008. We argue that a policy through which the central bank only allocates sufficient liquidity to allow banks a smooth fulfillment of their reserve requirements does not accommodate shocks to the aggregate reserve demand (Chapter 2). Therefore, an increase in aggregate reserve demand resulting from detrimental shocks to the financial systems' stability leads to an increase in the equilibrium rate in the primary money market and supposedly also to higher rates in secondary money markets. This, in turn, may destabilize liquidity-short banks aggravating tensions in the financial system. Hence, a liquidity-neutral allotment policy gives rise to self-enforcing liquidity crises. Second, this study discussed the issue of how the European Central Bank could perform its MRO auctions after the crisis (Chapter 3). In this regard, we point out that the Dutch or competitive auction format, as recently conducted by the Federal Reserve System in its term securities lending facility (TSLF) could be an alternative to the ECB's standard variable rate tender. In the competitive auction format, the probably destabilizing MRO spreads, which we find in our analysis are always zero because each successful bidder pays simply a uniform rate, i.e. the stop-out rate. Third, the apparent effectiveness of the net increase in outstanding open market operations with maturities at one, three, six, and twelve months opens up the possibility that they might become part of the monetary toolkit during normal times (Chapter 4). And fourth, using the example of the Swiss National Bank, we elaborated on the features associated with a longer-term interest rate as the operational target (Chapter 5). In general, shifting the emphasis from the overnight rate towards longer-dated term money market rates provides a central bank with sufficient leeway to deal with financial shocks without having to declare a change in the stance of monetary policy. Both the overnight rate and a longer-dated money market rate targeting might lead to similar outcomes in normal times, when large shocks are absent and spreads between interbank money market rates are low and stable. During financial crises, however, the Swiss example suggests that a three-month rate targeting, for instance, might be more successful in keeping risk premia in money markets relatively low.

There are many open issues, which could not be dealt with in this thesis. For instance, the crisis has raised serious question marks about the policy of benign neglect towards asset-price booms. The trend of the ongoing debates in the policy-making and academic circles seems to move towards the development of macro-prudential devices that directly detect potential incentive distortions and market failures. But, how such tools may be implemented in practice and how they are linked to monetary policy are the challenges of future research. Similarly, the crisis has revealed that price stability and financial stability are not necessarily natural bedfellows where the successful achievement of one facilitates the attainment of the other. Investigating this relationship in more detail may be another natural avenue for future research. Clearly, the challenges currently faced by the European banking sector reveal many other additional research fields, which require further investigation. Given the fundamental role of banks in most European countries, the future of the banking sector in the post-crisis environment is an issue of crucial importance for our economic welfare. Hence, there is much work to be done and even more to understand before we can return to 'normal' times. In this respect, it seems to be applicable today more than ever what James Tobin said exactly 30 years ago about the Great Depression:

"The crisis triggered a fertile period of scientific ferment and revolution in economic theory."
(James Tobin, 1981)

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