The Manipulation Potential of Libor and Euribor

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Abstract

The London Interbank Offered Rate (Libor) and the Euro Interbank Offered Rate (Euribor) are two key benchmark interest rates used in a plethora of financial contracts. The integrity of the rate-setting processes has been under intense scrutiny since 2007. We analyze Libor and Euribor submissions by the individual banks and shed light on the underlying manipulation potential for the actual and several alternative rate-setting procedures. We find that such alternative fixings could significantly reduce the effect of manipulation. We also explore related issues such as the sample size and the particular questions asked of the banks in the rate-setting process.

Keywords: Money markets, Libor, Euribor, manipulation, collusion

JEL classification: G01, G14, G18

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1 Introduction

One of the most important developments during the depths of the global financial crisis following the collapse of Lehman Brothers on September 15, 2008 was the discussion of the possible manipulation of the London Interbank Offered Rate (Libor) and its financial cousin, the Euro Interbank Offered Rate (Euribor), two key market benchmark interest rates. Although there had been prior conjectures of this possibility, new reports received heightened attention against the backdrop of jittery financial markets following the Lehman bankruptcy. Since spot and derivatives contracts with notional amounts running into the hundreds of trillions of dollars are linked to Libor and related benchmarks, any serious questions about the integrity of these rates could potentially cause massive chaos in global markets (see, e.g., the discussion in Wheatley (2012b)).

Given the nervousness in the market at the time, the British Bankers' Association (BBA) and the Bank of England (BoE) tried to reassure the market about the integrity of the rate-setting process. Although the attention of market participants shifted elsewhere for a while, there were persistent rumors, and even press reports, about the investigation, and possible prosecution, of the panel banks that submitted quotes to the BBA. The matter resurfaced in the financial headlines in the summer of 2012, when the Commodities and Futures Trading Commission (CFTC), the futures markets regulator in the United States, announced that it was imposing a $200 million penalty on Barclays Bank plc for attempted manipulation of, and false reporting concerning, Libor and Euribor benchmark interest rates, from as early as 2005.[1] As part of the non-prosecution agreement between the US Department of Justice and Barclays, communications between individual traders and rate submitters were made public, providing evidence of the manipulation of the reference rates on particular days. The results of an independent review led by Martin Wheatley, discussing potential changes to the Libor

[1] In December 2012, UBS AG also settled for a substantial penalty of $1.5 billion as a consequence of its role in manipulating global benchmark interest rates. More recently, Rabobank has agreed to a $1 billion settlement and RBS to total payments of more than $612 million. In addition, Barclays and Deutsche Bank face private law suits, and several bankers involved in the scandal have faced criminal charges. Several banks have admitted to wrongdoing regarding Yen Libor, and the European Union antitrust commission has initiated proceedings against several banks for collusion to manipulate financial benchmarks, fining six leading institutions $2.3 billion in December 2013.

benchmark rates at a general level, were presented in the UK in September 2012. Investigations in different jurisdictions, some of which started in 2009, are still ongoing.

In this paper, we analyze the individual submissions of the panel banks for the calculations of the respective benchmark rates (the "fixings"), in detail, for the time period January 2005 to December 2012.[2] In particular, we explore the statistical properties of these contributions and discuss the *potential effect* of manipulation by panel members, quantifying their possible impact on the final rate. In line with the argument of Kyle and Viswanathan (2008), we define manipulation to be any submission that differs from an honest and truthful answer to the question asked of the panel banks.[3] Furthermore, we explicitly take into account the possibility of collusion between several market participants. Our setup allows us to quantify such effects for the actual rate-setting process in place during our sample period, and compare it to several alternative rate-fixing procedures. Moreover, we can determine the effect of the panel size on manipulation outcomes. These results allow us to comment on important details of the rate-setting process, as well as on broader questions, such as the use of actual transaction data as an alternative information source.

A dispassionate appraisal of the events of the past few years and the discussion among market professionals, journalists and regulators suggests that two conceptually distinct issues became conflated in the heat of the discussion. The first relates to the potential for manipulation of Libor and Euribor — which are both determined by similar methodologies, but subject to the supervision of different bodies — under the current method of eliciting quotes from a given panel of banks. This issue naturally leads to a discussion of how the effect of manipulation might be mitigated, if not eliminated, by the use of an alternative definition of the rate, without altering the method of collecting the basic data from the panel of banks. The second and logically separate issue relates to changing the nature of the data themselves, for example, by only collecting data on *actual* transactions rather than using submitted quotes and, thus, introducing greater transparency and reliability into the process. The latter would be a much more fundamental change, and raises additional questions about how the liquidity of the rates

[2]The choice of the end date is dictated by changes in the procedure implemented as a consequence of the Wheatley report in 2013.

[3]Kyle and Viswanathan (2008) define manipulation as any trading strategy that reduces price efficiency or market liquidity.

for different maturities and currencies would be affected under the restriction of being based on transactions data.[4]

Within the context of the current rate-setting process, there are three factors that potentially affect the cross-sectional and time-series variation in the submissions, which, in turn, influence the computation of the trimmed mean used to set the rate. The first is the variation in the credit quality of the banks represented by the panel. Depending on the particular question asked of the panel banks, the rate submitted by a bank reflects, to a certain degree, the credit risk premium built into the borrowing rates.[5] If the banks have very different credit qualities in the judgment of the market, the rates submitted could reflect this variation. The second is the variation in the liquidity positions of the banks in the panel, which reflect their need for additional funding. If some banks are flush with funds of a given maturity in a currency, while others are starved of them, the rates they submit for this currency/maturity should be very different, even if their credit standings are similar. The third is due to the potential manipulation of the rates, as has been alleged and even demonstrated in at least some cases, by regulatory and legal action. Since it is impossible to disentangle the effect of manipulation from the credit risk and liquidity effects, without detailed data on the other two effects, we address questions based solely on the contribution data, relating to the potential for manipulation, given the historical pattern of rate submissions taking the unobserved credit risk and liquidity factors as given.

In this paper, we focus the presentation on three representative rates, Australian Dollar Libor (AUD Libor), US Dollar Libor (USD Libor) and Euribor, for the three-month tenor. The results for all other currencies and tenors are reported in summarized form. The purpose of choosing these three rates for our empirical analysis is to gain an idea of the extent to which the panel size, as well as the rate-setting process and the question asked of the panel banks, affects the final rate that is set. The number of panel banks is smallest for AUD Libor (7 banks) and largest for Euribor (42 banks), with USD Libor lying in between (18 banks).[6] Also, the questions asked for Euribor and Libor submissions are quite different, as will be discussed later on.

[4]In 2014, the Market Participtants Group on Reforming Interest Rate Benchmarks lead by Darrell Duffie submitted its final report discussing various of these issues, see Market Participants Group on Reforming Interest Rate Benchmarks (2014).

[5]See Section 2 for details of the underlying questions used in the rate-setting process.

[6]These panel sizes correspond to the last day of the sample period, i.e., December 31, 2012.

Our empirical analysis consists of three parts. First, we examine how closely individual submissions are related to the final rate that is set. Specifically, we estimate how often an individual bank's submission is below, within, and above the window that is used for the calculation of the trimmed mean. Furthermore, we analyze the time-series evolution of individual submissions with respect to the final rate. Second, we compute the effect on the rate of actions by one bank seeking to move the rate in the direction it desires.[7] We do this by setting the lowest submission on a given day equal to the highest one. The difference between the observed (historical) rate and the new resulting benchmark rate is our measure of the potential for manipulation.[8] We repeat this exercise for collusive action by two or three banks aiming to move the rate in their favor.[9] We analyze the differences in the effects of manipulation for different panel sizes and methodologies used to elicit rate submissions. Third, we quantify such effects for alternative rate-fixing procedures that have been discussed in the literature, in the press, or by regulators (see, e.g., Wheatley (2012a)) as well as some other alternatives that we propose. These methodologies include both *static*, relying only on the submissions from the same day, and *dynamic* approaches, incorporating submissions from the same and prior days. Of course, changing the calculation methodology also has an impact on the final rate. Thus, we also evaluate the effect of a methodology change on the final reference rate.[10]

Analyzing the individual submissions, we find that the range between the lowest and highest submissions is 11.73 bp for 3M AUD Libor, 13.29 bp for 3M USD Libor and 16.61 bp for 3M Euribor, on average. During the crisis these ranges are significantly greater peaking around 100 bp. Although economically significant, these differences are much smaller compared to the reported cross-sectional variation in CDS spreads with ranges of around 200 bp during the crisis years, see e.g. King and Lewis (2014). Interestingly, the composition of the set of panel banks whose submissions fall within the calculation window, after eliminating contributions at the highest and lowest ends, is very volatile. For the 3M AUD and 3M USD Libor panels, the submissions of most panel banks are within the calculation window around 50% of the time.

[7] The bank may wish to do so either to influence the market's perception of its credit quality or its liquidity, or to influence the profitability of its existing trading positions linked to these reference rates.

[8] See Section 5.2 for more details.

[9] Note, that this analysis is similar to Frunza (2013) who focus on showing *cartel-type* manipulation during the crisis for USD Libor based on its relation to US Treasury rates and CDS spreads. However, our setup is concentrated on potential individual manipulations.

[10] See Duffie and Stein (2015) for a discussion of benchmark rates.

For the Euribor panel, this figure is around 70%. Thus, the banks reporting the highest and lowest rates often change over time. Furthermore, we show that banks that are not in the calculation window switch regularly between being below and being above it. Thus, actual manipulations may have used the full range within the observed submissions without risking immediate detection.

To address our main research question, we focus on the potential effect of manipulation on the rate-setting process. Taking the observed submissions as given, we quantify the effects on the final rate of one, two or three banks changing their submissions in order to manipulate the rate in a certain direction. Our results clearly document that, although a trimmed mean is used, even manipulation by one bank could result in an average rate change of 1.16 bp (3M AUD Libor), 0.48 bp (3M USD Libor) or 0.17 bp (3M Euribor). Obviously, the collusion of several banks accentuates this effect: three banks could have an effect of 3.50 bp (3M AUD Libor), 1.61 bp (3M USD Libor) or 0.53 bp (3M Euribor). These effects are again higher during the crisis.[11] Given the tremendous sizes of the outstanding amounts of spot and derivatives contracts linked to these reference rates, banks can profit even from basis point changes.[12] Furthermore, these results clearly show that panel size plays a crucial role in the potential effect of manipulation. Euribor has the highest number of contributing banks (42 vs. 7 and 18) and the potential to manipulate it is considerably smaller than that for 3M AUD Libor and 3M USD Libor.

In addition, we analyze the potential effect of the manipulation of alternative static and dynamic rate-setting processes. In the static setup, the final rate is calculated based on the individual submissions of the current day (as applied in the currently used trimmed mean approach). Here, we consider two actual alternatives — the median of the submitted rates and a random draw[13] — and compare the effects to those obtained when using the untrimmed and trimmed mean. We confirm that, as expected, the use of an untrimmed mean leads to the highest potential for manipulation. Compared to the trimmed mean, the random draw alternative does not reduce the average effect of potential manipulation; indeed, the outcome becomes more

[11]Note, that we do not address the question of whether rates were too low during the crisis as such potential cartel-type manipulations affecting all rates can only be shown based on other financial market data, see Frunza (2013) and King and Lewis (2014), for example.

[12]For example, as of September 30, 2008, Deutsche Bank calculated that it could make or lose 68 million euros from a basis point change in Libor or Euribor. A Wall Street Journal article claimed that the bank made $654 million in 2008, profiting from small changes in these benchmark interest rates (see Eaglesham (2013)).

[13]This methodology was proposed by Wheatley (2012b).

volatile. Interestingly, the use of the median of the submitted rates, an extreme version of the trimmed mean, substantially reduces the possible impact of manipulation. The effect on the final rate is approximately one third lower than for the trimmed mean and random draw methodologies. Thus, we find evidence that switching the rate-setting process to the median rate, a relatively simple change, could substantially reduce the potential for manipulation in most cases.

In the dynamic setup, we first present approaches calculating the final rate based on submissions of the current day (as in the static approaches), while additionally using the time-series of past submissions to detect outliers on this day. In particular, we test alternative rate-setting methods that eliminate outliers based on the absolute changes in the individual submissions compared to the previous submissions of the banks. We present results where we use the same number of outliers as in the current setup, but combine outlier detection based on the cross-section and time-series of submissions, in equal proportions. We then combine the dynamic outlier elimination with the trimmed mean and median, to calculate the final rate, and show the resulting potential manipulation effects. Interestingly, we find that the manipulation effects using such dynamic methodologies are up to 50% lower than those using their static counterparts. In particular, combining time-series outlier elimination with the median of the remaining submissions results in the lowest manipulation potential overall.

In addition, we analyze whether using the submissions of multi-day windows for the calculation of the final rate based on static or time-series outlier detection can reduce the manipulation potential. Obviously, the effect of individual manipulations, given a certain manipulation frequency, will decrease, when the length of the multi-day window is increased. However, there is a clear tradeoff involved as new information is incorporated more slowly and, thus, the final rate might deviate significantly from the actual fixing (see, e.g., Duffie et al. (2013) for a discussion of sampling noise over multi-day windows based on a subset of Libor transactions). We use multiple-day windows of up to five days. As expected, we find significant reductions concerning the manipulation potential, e.g., using the static trimmed mean approach based on a five day average reduces the potential from 0.48 bp to 0.11 bp for 3M USD Libor. However, this decrease in the manipulation potential comes with a significant deviation of the final rate from the original rates that may outweigh the positive effect of the reduction. Interestingly, we find that times-series outlier detection without multi-day windows provides similar reductions of the manipulation potential without the negative effects on the resulting rates compared to applying static approaches using multi-day sampling.

It should be noted that a potential change in the calculation mechanism may lead to a new equilibrium and, thus, may change the behavior of banks when deciding on their respective submissions. In particular, time-series outlier detection and multi-day windows might increase manipulation frequencies as a reaction to the decreasing effect of manipulation. For example, dynamic outlier detection might make it profitable to manipulate rates on consecutive days to preclude the possibility that a certain submission is eliminated because of its absolute change. However, such increased manipulation frequencies could also increase the cost of manipulation as detection becomes more likely. As we do not model this cost structure, we do not evaluate the performance of the presented alternative measures along these lines.

Overall, we find that both the panel size and the calculation methodology influence the manipulation potential, i.e., a large panel size, the use of median rates and outlier elimination based on large daily changes in the submissions, substantially reduce the possible impact individual banks can have on the final rate. Moreover, we analyze the effects of these alternative methods on the level and volatility of the rate itself, and find the possible impact on Libor and Euribor to be much smaller compared to the reduction of the manipulation potential that we document. In contrast, using multi-day windows mitigates the manipulation potential as well; however, we find significant deviations of these reference rates from the original rates.

Although a change in the calculation methodology could be implemented fairly easily, increasing the panel size for the Libor rates, under the current setup, could be more challenging. Given that banks are explicitly asked about their own funding rate for Libor, enlarging the sample might introduce even more heterogeneity, in terms of credit, liquidity, and outstanding positions, across the panel banks. Thus, increasing the sample size might only be reasonable when asking about the money market funding costs of a (hypothetical) prime bank, as in the case of the Euribor.

2 Description of the Rate-Setting Process

In this section, we outline the institutional details and the methodology for the calculation of the reference rates that have been applied throughout our observation period.[14] Overall, the general methodologies used for calculating Libor and Euribor are broadly similar. However, they differ in several ways that could affect the possible impact of manipulation. Both Libor and Euribor reference rates are published daily, for a range of maturities, and are based on submissions from a pre-defined set of panel banks.

The Libor reference rates are set under the auspices of the BBA, with the assistance of Thomson Reuters, the calculation agent.[15] Reference rates are published for ten currencies and fifteen maturities (or tenors).[16] On every London business day between 11:00 and 11:10 a.m., the individual submissions are received by the calculation agent. For each currency, there is an individual panel of banks contributing rates for all tenors. (A bank may submit rates for multiple currencies.) The smallest panel size is 6 banks, for SEK and DKK, and the largest panel is 18 banks, for USD. A bank has to base its contribution on answering the following question:

Libor Question: "At what rate could you borrow funds, were you to do so by asking for and then accepting inter-bank offers in a reasonable market size just prior to 11 am?" (British Bankers' Association, 2012)

In the then prevailing routine, all panel banks submit contributions every day. Based on the individual submissions, a trimmed mean is calculated for each currency and tenor by discarding the top and bottom 25% of the contributions. The final rates are rounded to five digits and distributed by mid-day London time.

[14]Note that changes to this setup have been implemented in 2013, based on the Wheatley report (Wheatley, 2012a). Initial changes have been based on the discontinuation of certain Libor currencies and tenors. As our data set ends *before* the implementation of these recommendations, we present here the Libor calculation that corresponds to our sample period prior to 2013.

[15]Note that the administration of the Libor rates was transferred by the BBA on January 31, 2014 to ICE Benchmark Administration Limited, formerly known as NYSE Euronext Rates Administration Ltd.

[16]The ten currencies are the British Pound (GBP), US Dollar (USD), Japanese Yen (JPY), Swiss Franc (CHF), Canadian Dollar (CAD), Australian Dollar (AUD), Euro (EUR), Danish Krone (DKK), Swedish Krona (SEK) and New Zealand Dollar (NZD). The fifteen tenors comprise O/N (or S/N), 1W, 2W, and 1M, 2M, ..., 12M. Following the recommendations of the Wheatley review, all maturities for NZD, DKK, SEK, AUD and CAD were discontinued over the course of the first half of 2013. By the end of May 2013, all tenors except for O/N (S/N), 1W, 1M, 2M, 3M, 6M and 12M had been discontinued for the remaining five currencies (CHF, EUR, GBP, JPY and USD).

The Euribor reference rates are set under the aegis of the EBF. Again, Thomson Reuters is the screen service provider, and is responsible for computing and also publishing the final rates. Reference rates are available for fifteen tenors (1W, 2W, 3W, 1M, 2M, ..., 12M). Panel banks are required to submit their contributions directly, no later than 10:45 a.m. CET on the day in question. On December 31, 2012, the panel consisted of 42 banks. A bank has to base its contribution on the following implicit definition:

Euribor Question: "Contributing panel banks must quote the required euro rates to the best of their knowledge; these rates are defined as the rates at which euro interbank term deposits are being offered within the EMU zone by one prime bank to another at 11.00 a.m. Brussels time." (European Banking Federation, 2012)

Not all panel banks have to submit contributions to the reference rates on each day. Under normal conditions, at least 50% of the panel banks must quote in order for the Euribor to be established. Based on the individual submissions, a trimmed mean is calculated for each tenor by discarding the top and bottom 15% of the contributions. The final rates are rounded to three digits and are distributed by 11:00 a.m. CET.

Both Libor and Euribor are ostensibly designed to be robust to outliers. This is done using the trimmed mean approach, described above: a specific number of contributions are discarded before the final fixing is calculated as the average of the remaining contributions. The exact number of excluded panel banks depends on the original panel size, but can be approximately 50% (top and bottom 25%) for Libor, and 30% (top and bottom 15%) for Euribor. The number excluded for different panel sizes, and the rounding approaches applied, are shown in Tables 1 and 2.

Obviously, this approach is designed to make Libor and Euribor robust with respect to outliers. However, even a single contributing bank can manipulate the final fixing by submitting a high or low rate. For example, if just one bank changes its contribution, e.g., instead of truthfully reporting a low rate it reports a high rate, then, even though this contribution will be discarded, it will nonetheless shift the calculation window, i.e., the set of banks that contribute to the trimmed mean, by one bank, in the direction of including a panel bank with a higher rate, and discarding one with a lower rate.

Table 3 shows this effect based on an example of the rate-setting for the three month AUD Libor on the last day of our sample, December 31, 2012. In the first row, we show the contributions submitted by the seven panel banks on that day. For the given panel size, the lowest and highest contributions are excluded in the trimming process. Thus, AUD Libor is calculated as the average of the contributions of the remaining five banks, i.e., banks 2 to 6. In the second row, we show the effect of a change in a single contribution on the final Libor fixing. If the bank with the lowest contribution instead submits a contribution equal to that of the bank with the highest contribution, then the calculation panel used to determine the Libor fixing will be shifted. Bank 1 will move to the top of the (sorted) panel and its contribution will be excluded during the trimming process. Instead of Bank 1, Bank 2 will now be excluded on the lower end, and Bank 7 will enter the calculation panel. Consequently, in the calculation of the average, the contribution of Bank 2 (3.23%) will be replaced by the contribution of Bank 7 (3.30%). This will increase the Libor fixing by 1.4 bp.

This example applies to both the Libor and the Euribor, as both use a trimmed mean approach. However, two important interconnected differences should be highlighted when comparing Libor and Euribor rates. First of all, we can observe fairly large differences in the panel sizes. Whereas Euribor relies on 42 banks, some Libor rates are only based on as few as 6 banks and, even for USD, the currency with the largest panel size for Libor, the panel size is only 18 banks.[17] The second difference is related to the different questions asked of the banks for Libor and Euribor. Whereas Libor is supposed to reflect the average of all the panel banks' *individual* borrowing rates, Euribor is designed to represent the rate at which deposits are offered from one (hypothetical) prime bank to another.[18] In the absence of manipulation, the Libor approach has the advantage that contributions should have a one-to-one relation with the rates applying to the actual transactions of a particular bank. However, this comes with the disadvantage of incorporating the individual credit and liquidity statuses of the panel banks into the reference rate. Thus, for Libor to be meaningful, the selection of the panel banks is more crucial than it is for Euribor. Of course, this limits the number of banks that can potentially be included

[17]Since the scandal became public, many banks have stopped contributing to Euribor, which reduced the panel size to 20 banks.

[18]More recently, questions have been raised about the precise definition of a "prime bank" and the need to make it more explicit.

in the panel. Therefore, it is particularly interesting to compare the potential to manipulate between Libor and Euribor.

3 A Review of the Literature

Libor and similar benchmarks have recently received considerable media attention. In particular, one report does provide some early, indirect evidence on manipulation: In a Wall Street Journal article published shortly after the onset of the financial crisis, Mollencamp and Whitehouse (2008) claim that banks have been submitting low Libor rates to avoid signaling their own deteriorating credit quality. The authors use CDS spreads to construct an alternative benchmark and conclude that, compared to these estimates, the actual Libor rates have been too low. Along the same lines, King and Lewis (2014) analyze the relation of Libor submissions and CDS spreads as well, accounting for the possibility of strategic misreporting.

However, using CDS data might lead to noisy estimates, since CDS spreads typically reflect longer term rates, and hence are not necessarily perfect proxies for short-term credit quality. Moreover, as pointed out in Abrantes-Metz et al. (2012), there are other factors, such as liquidity, that influence CDS spreads, particularly in crisis periods. Given these issues, Abrantes-Metz et al. (2012) focus on the ordinal information contained in CDS spreads and check whether contributors with high CDS spreads also report higher Libor rates. In addition, they compare Libor to other short-term funding rates, e.g., the federal funds effective rate. They do find patterns that hint at possible abnormalities, but conclude that there is no clear evidence to support the allegation of the manipulation of Libor rates. In another study, however, Abrantes-Metz et al. (2011) suggest that the conjecture regarding abnormal levels of the aggregate Libor calculation is supported by the data: Libor rates do not follow Benford's law for the second-digit distribution.

Snider and Youle (2014) expand on the results provided by Mollencamp and Whitehouse (2008) and focus on a second — potentially even more important — incentive for manipulation. Given the large notional volumes referencing Libor (and, of course, other reference rates like Euribor), panel banks could have substantial incentives to manipulate Libor submissions so as to move the fixing in their favor. Snider and Youle (2014) argue that, given the incentives for manipulation due to portfolio effects, a bunching effect around particular points should be observed. In other words, contributions just above or below the cut-off points used for the trimming procedure should be observed with higher frequency.[19] The authors also find evidence of this particular behavior. Based on similar ideas, Gandhi et al. (2016) estimate a crude proxy of weekly Libor positions of the submitting banks, and show a relation between these positions and the submissions. Abrantes-Metz et al. (2012) analyze the participation rate of each individual panel bank, i.e., the frequency with which a bank's quote is not discarded in the outlier elimination process, and find that, from August 2007 onwards, the composition of the panel within the window is less stable than before that date. This is interpreted as a potential sign of manipulation. Frunza (2013) focuses on showing cartel-type manipulation, for USD Libor, during the crisis, based on its relation to US Treasury rates and CDS spreads. Furthermore, Fouquau and Spieser (2015) use tests of non-stationarity, analyzing breaks in the data during the crisis period to detect manipulations, and threshold regression models, to determine periods of abnormal behavior. This analysis allows the identification of groups of banks that followed different submission policies before and after the breaks.

The second strand of the literature deals with possible reforms and improvements to the Libor rate-setting process. Following the alleged Libor manipulation by several large investment banks, Martin Wheatley was requested by the UK government to lead an expert group tasked with identifying improvements and amendments to the current Libor fixing process, including institutional details surrounding the Libor contribution process. The initial discussion paper (see Wheatley (2012b)) raised several questions that have triggered strong responses from the industry. The final version of the Wheatley Review (Wheatley, 2012a) argues very much in favor of reforming the current Libor system rather than replacing it with a new benchmark. It is suggested that the number of tenors and currencies of Libor submissions be reduced, and that panel banks be required to keep records of their actual transactions to permit validation by regulatory authorities. Furthermore, the impact of the panel size and alternative rate-setting methods are discussed at an abstract level, but not with any detailed empirical analysis. In contrast to these suggestions, Abrantes-Metz and Evans (2012) propose changes that would increase the importance of transaction-based data in the rate-setting process, by forcing panel

[19] The theoretical explanation for this effect is based on the costs of misreporting, and the panel banks' ability to predict the cut-off point. Thus, given that lowering the Libor submissions below the predicted cut-off point would only lead to higher costs, with no additional manipulation effect, banks will only manipulate their contributions to this extent.

banks to commit to trading at the reported rates. However, it will only be possible to evaluate this proposal empirically, once detailed transaction data become available. Along similar lines, Duffie et al. (2013) study the potential of a calculation method based on transactions data and a multi-day sampling window, using a small sub-sample of transactions identified based on Fedwire data, where this identification is based on an algorithm presented by Kuo et al. (2013). Another group of papers presents theoretical models analyzing the strategic decision of a submitting bank. Chen (2013) explores the interaction between the dispersion of a bank's borrowing costs and its submission, incorporating the signaling of creditworthiness. Coulter and Shapiro (2013) propose a new Libor mechanism including a second stage in which panel banks can challenge the Libor submissions of other banks. In their framework, this mechanism leads to truthful submissions. In a contemporaneous paper, Youle (2014) provides a model based on a noncooperative game of incomplete information for the three months USD Libor. The paper shows, within this setup, that a change to the median instead of a trimmed mean can reduce manipulations. However, the paper ignores a salient feature of the manipulations that have been uncovered: the collusion between banks. Duffie and Dworczak (2014) develop a robust estimator for transactions-based benchmark rates.

In this paper, we focus on the quantification of the potential effects of manipulated individual contributions on the final rate, explicitly taking into account the possibility of collusion between several banks. Furthermore, we test, in detail, how these effects change when alternative rate-setting procedures are implemented, including the suggestions mentioned in the Wheatley report, and additionally using methodologies based on the time-series of submissions. No other paper has yet extensively analyzed the potential impact of manipulation on the final rate, to the best of our knowledge. We emphasize that we refrain from modeling the underlying incentive structure for manipulations, e.g., by applying a game theoretic model, as the incentive to manipulate in a realistic setup has to be based on the position of the bank or even of the individual trading desks (as documented by released communications) and this information is simply not available.

Although Libor, as well as Euribor, are, in principle, designed to be more robust[20] to manipulation attempts than simple, untrimmed averages, they are not immune to manipulation attempts by even a single bank, as explained in Section 2.[21] Clearly, the selection of the panel and the rate-setting process influence the manipulation impact that this procedure can have on the benchmark interest rates. We fill the gap in the literature by quantifying the potential impact of manipulation on the current procedure, and the reduction in this impact that would be seen if alternative procedures were used.

4 Data Description

In this paper, we focus our discussion on three reference rates in order to analyze the potential effects of manipulation: AUD Libor, USD Libor and Euribor. These rates differ substantially in terms of their respective contributing bank panel sizes, spanning the differences across currencies, allowing us to study this aspect in detail. We choose the AUD Libor as it is a liquid currency with one of the smallest panel sizes of all the Libor rates (7 banks, on December 31, 2012).[22] The USD Libor has the largest panel size of all Libor rates (18 banks) and is one of the most widely referenced rates in global markets. The third reference rate we investigate is Euribor, which features a very large panel size (42 banks), compared to all Libor rates. Moreover, Euribor panel banks are not asked to contribute their own funding rate but rather that of a *hypothetical* prime bank. Thus, whereas Libor contributions potentially differ more because of individual panel banks' credit quality and liquidity, Euribor contributions should essentially only differ because of each panel bank's estimation error in determining the "true" funding rate of a prime bank.

For these three reference rates, we focus on the three-month tenor. This maturity is an important reference point for many derivatives contracts and loans that are linked to these rates.

[20] In general, robust statistics are concerned with methods that can deal with "wrong" measurements. For estimators of location parameters, this often means the ability to detect "outliers" and avoid their impact on the estimation result. However, it is difficult to apply these methodologies directly to the context of manipulation for two reasons. First, manipulated submissions can have an impact without being outliers. Second, manipulated submissions that are correctly identified as outliers can also have an impact.

[21] Abrantes-Metz and Evans (2012) also show this with a simple example.

[22] The panel sizes for DKK and SEK are even smaller, but these currencies are not as widely used as the other currencies. In fact, Libor rates for both currencies will be discontinued following the implementation of the recommendations of Wheatley (2012a).

Thus, manipulation incentives might be particularly pronounced for this tenor. However, we comprehensively analyze all tenors and currencies and present the results in summarized form.

Our data set comprises the daily individual contributions of all the panel banks and the final reference rates, for the time period from January 2005 to December 2012.[23] Data for the Libor rates and contributions are obtained from Bloomberg, while the Euribor rates and contributions are published by the EBF on its Euribor website. We exclude a few days with data errors, for which we cannot reproduce the final fixings using the individual contributions provided by Bloomberg or EBF. The most common reasons for these discrepancies are missing contributions from individual panel banks, and apparent data errors. In total, we have $2,020$ days available.[24]

As the ongoing investigations indicate that manipulation attempts may have commenced as early as 2005, we cover the whole relevant time period, including a few calm years prior to the beginning of the recent financial crisis, and the years since. Thus, our data set offers the possibility to study manipulation effects based on different panel sizes, the two underlying funding rate questions, and varying economic conditions.

5 Results

5.1 Descriptive Statistics

This section provides summary statistics for the reference rates and the contributions submitted by the individual panel banks for the 3M AUD Libor, 3M USD Libor and 3M Euribor. Figures 1–3 show the time-series of the three reference rates. We present, within these figures, the cross-sectional standard deviation of the individual contributions, the range (i.e., the difference between the highest and lowest contribution), and the panel size on each day.[25]

The three time-series of the reference rates paint a similar picture, with an increase in the interest rates from 2005 until mid-2007, and a rapid decrease following the financial crisis.

[23] As a result of the reform suggestions, several changes to the computation and publication of Libor have been implemented in the course of 2013. For example, the NZD Libor was discontinued after February 2013. Starting in July 2013 the publication of individual submissions for Libor rates is delayed by three months. Thus, we end our sample period before these changes in the Libor procedure were implemented. Due to data quality issues and missing panel banks, we do not use data for the time-period before 2005.

[24] We exclude 2 days for the AUD Libor, 17 days for the USD Libor, and 37 days for the Euribor, due to the aforementioned missing data and apparent errors.

[25] The panel size represents the actual number of contributions submitted on a given day.

Analyzing the individual contributions, we find that, for AUD and USD Libor, the panel sizes stay basically unchanged; it is only at the end of the observation period that the panel size for AUD reduces from 8 to 7 banks, and that for USD Libor increases from 16 to 18 banks. Interestingly, the number of banks actually submitting to the Euribor panel on a given day is more volatile over time, for two reasons: First, the panel size changes more often and, second, not all banks make submissions every day. However, even the smallest actual panel contains 37 banks, which is twice the size of the panel for USD Libor.

Analyzing the cross-sectional standard deviation and the range of quotes, we find that, particularly during the financial crisis, the dispersion of the individual contributions is quite high. For example, around the time of the Lehman default, the range of quotes is above 100 bp for 3M AUD and 3M USD Libor, and just below this value in the case of 3M Euribor. Considering the full sample period, the range between the lowest and highest submissions is 11.73 bp for 3M AUD Libor, 13.29 bp for 3M USD Libor and 16.61 bp for 3M Euribor, on average. The standard deviations show virtually identical findings. Note that, even for 3M Euribor, the cross-section of contributions is volatile, even though all contributing banks submit their estimates of the funding costs for a hypothetical prime bank, in this case. Although economically significant, these differences are much smaller compared to the reported cross-sectional variation in CDS spreads, with ranges of around 200 bp, during the crisis years (see e.g., King and Lewis (2014)). Potentially, this may be because the submitted rates are more linked to short-term credit risk compared to longer term CDS spreads. In addition, banks may try to influence the market's perception of their credit quality by submitting lower rates.

Given that the cross-sectional contributions are quite well dispersed, a question arises as to whether the contributions of the individual panel banks become more stable over time. In this respect, it is particularly interesting to look at whether the relative position of one bank compared to the other banks changes over time. If the credit and liquidity risk of an individual bank, or its error in estimating the relevant funding costs, do not vary much over time, then manipulation attempts could be detected by identifying banks whose relative positions change dramatically, e.g., reporting a low rate one day and a high rate the next.

To analyze this issue, in Tables 4–6 we show the frequencies with which banks appear in the calculation panel (i.e., the bank's contribution is not discarded in the trimming process), for all panel banks and for all three reference rates, as well as the frequencies with which their submissions are below and above the calculation panel. All these frequencies are shown for the whole time period and for two subperiods: for the normal period from January 2005 to June 2007, and the crisis period from July 2007 to December 2012.

Overall, we find that banks switch regularly between being within the calculation panel and falling outside the panel and being discarded. Looking at the frequencies for the AUD Libor banks, UBS has the lowest frequency of being in the calculation panel, at 41%, and HSBC the highest, at 85%. Most of the banks are in the calculation panel on around 50% of all days, which is basically identical to the percentage of banks included in the calculation panel. Roughly the same result is found for USD Libor and Euribor. The only difference for Euribor is that the frequencies are generally higher, as only 30% of all submissions are discarded in this case. These results also hold, in general, when analyzing the two subperiods. However, here we find that, in the crisis periods, some banks are discarded from the calculation panel with higher frequencies.

Turning to the frequencies for being outside of the calculation panel, we find that banks often have similar frequencies for being above and being below. In other words, typically, banks show no pattern of being often discarded from the calculation panel because of reporting rates that are always too high or always too low. For example, for the AUD Libor, Deutsche Bank is below the panel in 19% of all cases, and above it in 26% of all cases. The results for USD Libor and Euribor are quite similar. Again, only in the crisis period do we find that some banks are below the panel more frequently than they are above it.

The reported frequencies provide a first indication of the time-series volatility of the individual contributions. However, the observed frequencies could arise because of long-term movements in the individual contributions. That is, a particular bank's contributions could be above the calculation panel for several months, then in the calculation panel for some months and, finally, below the other quotes. Thus, in the next step, we explore the day-to-day changes in the individual rates.

To analyze this issue, we explore the time-series of the ranks of the contributions and, furthermore, we plot the differences between the actual bank contributions and the final rate. Tables 7–9 present the means and standard deviations of the daily absolute rank changes for each bank for the three reference rates. Note that we have normalized the rank by the panel size so as to be able to compare the results across currencies. In other words, the highest contribution has rank one. Again, we present results for the whole time period and the two subperiods. Analyzing AUD Libor banks, the daily absolute rank change of a bank is around 13.5% of the panel size (e.g., HSBC has the lowest average rank change with 7% and HBOS has the highest with 18%). Thus, the daily change in rank is quite high for all banks. The standard deviation is around 15.8%, and shows the same variation as the mean across banks. These numbers are similar in both subperiods. However, we observe somewhat smaller average rank changes in the crisis period, of around 12.9%, potentially because of more pronounced differences in credit or liquidity risk. We find similar results for the USD Libor and Euribor panel banks. Overall, the observed rank changes indicate that virtually all banks have frequent rank changes. Figure 4 shows the time-series of the ranks for representative panel banks. We present two banks per reference rate, although the patterns for the other banks are similar. These time-series confirm that the rank of an individual bank's rate submissions tends to be quite volatile on a day-to-day basis.

Focusing on the differences between the actual bank contributions and the final rate, we define for every day, t, the spread over Libor/Euribor as the difference, $d_{i,t}$, between an individual submissions, $s_{i,t}$, of bank i, and the final interest rate fixing, f_t, on that day.

$$d_{i,t} = s_{i,t} - f_t \tag{1}$$

Figure 5 shows the time-series evolution of the spread over AUD Libor, USD Libor and Euribor for the same representative panel banks as used in the previous figure. The results confirm that individual panel banks' contributions are volatile and show a high degree of day-to-day variation. In addition, it happens rather frequently that banks go from being below the final fixing to being above it, from one day to the next.

Thus, actual manipulating banks may have used the full range within the observed submissions, without risking immediate detection. We use this finding when quantifying the potential effect of manipulation in our main analysis. Furthermore, given these results, we find a clear need for mandatory transaction reporting to a central data repository, with delayed public dissemination, to ensure greater transparency. This mechanism would be a first step toward validating individual rate submissions, and thus might allow a data-driven identification of manipulation.[26] Similar transparency projects have been implemented for different OTC markets in the last decade: In the US corporate bond market since 2004, the US municipal bond market since 2005, and the US fixed-income securitized product market since 2011, the reporting of all transactions by broker/dealers has been mandatory. Many studies have analyzed these transparency projects and documented the positive effects of increased transparency.[27] Thus, transparency in the underlying money markets would certainly foster confidence among market participants in the reliability of important benchmark interest rates.

5.2 A First Look at Manipulation

In this section, we quantify the effects of potential manipulation based on the actual rate-setting process currently in place. We present results for one bank seeking to move the rate in a particular direction, and then repeat this analysis for the collusive action of two or three banks. We analyze AUD Libor, USD Libor and Euribor, so that we can compare the effects on rate fixing of different sample sizes and the underlying questions asked of the panel banks to elicit their submissions.

We use the following approach to quantify the potential effects of manipulation: For each day, we start with the observed individual contributions made by the panel banks, as well as the actual rate fixing, on each day. Then, we change the lowest observed contribution, making it equal to the highest observed contribution, for the case of a manipulation by one bank (see Table 3 for an example).[28] The difference between the observed (historical) benchmark rate and the resulting benchmark rate, after changing this one contribution is our measure of the potential effect of manipulation. Of course, different approaches could have been chosen, e.g., by changing the lowest contribution within the calculation panel or the contribution in the center of the calculation panel (or by randomly drawing one contribution and changing it).[29] However, we think that our approach offers important insights, for two reasons: First, we are

[26] As a result of the investigations, several changes to the Libor mechanism have already been implemented. For example, many illiquid currencies and tenors have been discontinued, individual submissions are published with a delay and the administration has been transferred from the BBA to ICE Benchmark Administration Ltd.

[27] See, e.g., Bessembinder et al. (2006), Harris and Piwowar (2006), Edwards et al. (2007), Green (2007), Green et al. (2007), Goldstein et al. (2007), Friewald et al. (2012) and Friewald et al. (ming).

[28] Note that potential manipulation in the opposite direction, i.e., setting the highest contribution equal to the lowest value, results in essentially identical effects. Thus, the approach could also be interpreted as reversing actual manipulations and measuring the impact.

[29] We provide a set of robustness checks based on simulations analyzing the effect of strategic submissions and of pre-manipulated data in the Internet Appendix.

interested in the potential to manipulate the reference rate in a certain direction. This potential is obviously maximized at the lower and upper ends of the range of contributions. Second, given the substantial volatility we document in the individual contributions, we consider it reasonable to assume that, if manipulation is considered by a bank, it will make use of the full range of potential values in order to maximize its impact on the reference rate.[30] Note that we use the same approach when considering the manipulation potential for two or three banks, in that, here, we set the lowest two (or three) contributions equal to the highest observed contribution.[31]

Figure 6 shows the time-series of the impact of manipulation attempts by one, two and three banks, for the three reference rates. Our results clearly show that, even though a trimmed mean is used, a manipulation attempt by one bank has an economically significant effect: on average 1.16 bp for AUD Libor, 0.48 bp for USD Libor and 0.17 bp in the case of Euribor.[32] The reference rates are not robust to manipulation, even by a single bank, as discussed in Section 2. Thus, individual banks or particular traders within a bank can profit from the manipulation even without colluding with other banks. Of course, we find that (as expected) the effect of manipulation increases significantly when there is collusion between several banks. For example, the average effect for USD Libor increases to 1.01 bp (two banks) and 1.61 bp (three banks), respectively.[33] In addition, the time-series shows that the potential to manipulate became much more pronounced during the financial crisis, as the range of the individual contributions increased (as discussed in Section 5.1).[34] Thus, we find that the average manipulation effect of three banks in the time period January 2005 to June 2007, compared to the time period July 2007 to December 2012, is 1.25 bp versus 4.51 bp for AUD Libor, 0.16 bp versus 2.25 bp for USD Libor and 0.13 bp versus 0.71 bp for Euribor.[35]

[30] Note that we do not incorporate the banks' incentives to manipulate in the estimation of the measure for two reasons. As stated earlier, modeling the incentive structure would require us to know the precise exposure of each of the panel members to Libor or Euribor. However, this information is simply not available. Also, there are often multiple trading desks within a particular bank, with disparate exposures to the reference rate. Hence, there is no clear desirable direction for manipulation for the bank. This creates an additional challenge in analyzing the incentive effect, as the actual observed manipulations were often initiated by individual traders seeking to optimize their own position.

[31] Note that this analysis is similar to that in Frunza (2013), who focus on showing *cartel-type* manipulation during the crisis for USD Libor, based on its relation to US Treasury rates and CDS spreads.

[32] These effects are also statistically significantly different from zero at the 1 percent level using a one-sample t-test.

[33] These differences are statistically significant at the 1 percent level using a Student t-test.

[34] Note, that in our analysis we do not focus on possible cartel-type manipulation as, e.g., in Frunza (2013).

[35] These differences are statistically significant at the 1 percent level using a Student t-test.

In addition, these results allow us to discuss the effect of panel size on the potential for manipulation. We find the expected result that this potential is largest in the case of AUD Libor, at 3.50 bp for three banks, and smallest in the case of Euribor, at 0.53 bp, again for three banks. Thus, using larger panels to provide the information on which a reference rate is based reduces the potential for individual banks to manipulate the final rate. We will present a more detailed discussion of the panel size in the next section, after discussing the manipulation effects under alternative rate-setting processes. In Table 10, we present the manipulation potential based on three banks for all currencies and tenors. These results confirm the findings presented based on the 3M tenor of AUD Libor, USD Libor and Euribor.

Overall, we find significant potential to manipulate the reference rates under the current rate-setting process. Our results clearly document that even a single bank can have an important manipulation impact. However, this potential is particularly strong in the case of smaller panel sizes and where collusion with other banks is possible. Furthermore, we find that the manipulation potential was particularly strong during the financial crisis, as the range of the individual submissions increased due to increased heterogeneity among the panel banks with regard to credit and funding risk.

5.3 Static Alternative Rate Fixings

In this section, we analyze three alternative rate-fixing methodologies, and discuss how they influence the potential for manipulation. These alternative fixings are all *static*, in the sense that only the information from the submissions on a particular day is used to detect outliers, as is the case with the currently applied trimmed mean methodology. The first alternative is simply the untrimmed mean, which we include so as to have a simple, naive benchmark. In addition, we consider two other rate-setting processes as real alternatives to the present method, and focus our analysis of static alternatives on these results. We look at the median and a random draw of the individual contributions. The use of the median of the submissions is an obvious alternative, as it is the numerical value separating the higher half of a sample from the lower half, meaning that the importance attached to outliers is reduced. In the random draw approach, the individual submissions are first trimmed according to the current rules, and then one of the submissions in the calculation panel is randomly selected to represent the final rate for the day in question. The motivation behind this approach is to make it more difficult for manipulating banks to predict the final rate. Both methods are briefly mentioned in the Wheatley report (see Wheatley (2012a)) as potential improvements on the present rate-setting process. We report the results for the present process (the trimmed mean) in this section as well, to allow a direct comparison of the methods.

We use the same procedure to evaluate the effects of potential manipulation attempts under these alternative rate-setting procedures that we applied earlier for the trimmed mean. In other words, we change the one, two or three lowest contributions by individual banks, setting them equal to the highest observed contribution, and then calculate the resulting (manipulated) benchmark rate and compare it to the original rate according to the given rate-setting procedure. In the case of the random draw approach, we define the random number selecting the relevant submission to be the same in the original and the manipulated set. That is, the same position within the calculation panel is drawn for the manipulated set. Thus, we assume that the randomly drawn position is not influenced by the submitted values, which is a reasonable approach.

Table 11 reports the time-series averages and standard deviations of the manipulation effects. Starting with the manipulation effect of one bank, we find the following results: First of all, we can confirm that the untrimmed mean indeed offers the highest potential for manipulation, for all reference rates. For example, for USD Libor, the effect is 0.78 bp for the untrimmed mean versus 0.48 bp for the trimmed mean. Interestingly, we find that the median provides the smallest potential, for all reference rates: for example, for Euribor, we observe 0.08 bp for the median versus 0.17 bp for the trimmed mean.[36] The random draw method provides the same level of manipulation potential as the trimmed mean. However, the standard deviation of the manipulation potential increases, i.e., the outcome of a manipulation attempt becomes more volatile. For example, for AUD Libor, the standard deviation is 1.25 bp for the trimmed mean and 3.26 bp for the random draw.[37]

As mentioned in Wheatley (2012b), changing the rate-setting mechanism also affects the Libor itself. Thus, we compare the manipulation effects to the average impact on the final rate itself. For the 3M USD Libor, we find that the average daily difference between the trimmed

[36]The results are statistically significant at the 1 percent level using a two-sample Student t-test.

[37]The standard deviations are significantly different at the 1 percent level using an F-test for equal variances.

mean and the median is -0.02 bp, with a standard deviation of 0.39 bp.[38] Thus, the median yields a Libor that is, on average, marginally lower than the Libor calculated using a trimmed mean, i.e., the resulting rate is not biased in a certain direction. However, the standard deviation shows that moderate differences between the rates arise. Therefore, we analyze whether these differences arise because the median approach results in a more volatile rate. Thus, we compare how the daily variation of the 3M USD Libor (i.e., the change of Libor from day $t-1$ to t) is affected by the change of the rate-setting mechanism. To this end, we calculate the average of the absolute daily changes of the Libor, i.e. $|f_t - f_{t-1}|$, for the median and the trimmed mean. Using the median increases this average only slightly by 0.01 bp.[39] Thus, the impact on the rate itself (level and volatility) seems to be much smaller than the possible reduction of the manipulation potential.

Analyzing the manipulation effects in the case of collusion by two or three banks provides interesting insights as well. Focusing first on the USD Libor and Euribor, we find (as expected) that, for all static alternative rate-setting processes, the manipulation effects increase with the number of colluding banks. The increases from one to two or three banks are comparable to the increases discussed in the case of the trimmed mean (see Section 5.2). Furthermore, we find basically the same results as in the case of one bank when comparing the different rate-setting processes: The untrimmed mean offers the highest potential, whereas the median offers the lowest among the methodologies. Again, a random draw is comparable to the trimmed mean but with higher standard deviation. These findings provide two important results: First of all, the use of the median rather than the trimmed mean would reduce the manipulation potential significantly. That is, for USD Libor, in the case of two manipulating banks, the effect falls from 1.01 bp to 0.74 bp, and in the case of three banks, from 1.61 to 1.28 bp. For Euribor we find similar effects: the manipulation potential decreases from 0.35 to 0.18 bp in the case of two banks, and from 0.53 to 0.27 bp in the case of three banks. Second, panel size is an important driver of the manipulation potential under the alternative rate-setting procedures as well as under the prevailing procedure. For the median, in the case of two (three) banks, we find

[38]For each rate-setting methodology, we calculate the rate for each day of our sample period. We then calculate the difference between two approaches for each day, and average these differences over our sample period. Note that the mean difference is not statistically significantly different from zero.

[39]We also calculate these values for the three month AUD Libor and Euribor and find qualitatively similar results.

effects of 0.74 bp (1.28 bp) for USD Libor versus 0.18 bp (0.27 bp) for Euribor. Thus, we find smaller effects on the final rate for Euribor, where the largest panel is used. Again, all these differences are statistically significant at the 1 percent level, and we find much lower effects on the rates by changing the rate-setting mechanism, compared to the manipulation potential.

When analyzing the same potential in the case of collusion for AUD Libor, we find important differences that are related to the smaller sample size in this case. These differences allow us to discuss the alternative rate-setting procedures in more detail. The main difference between the findings is that, when three banks collude (which means three out of seven or eight banks manipulate, in the case of AUD Libor), the untrimmed mean provides the lowest potential, whereas the median provides the highest potential to manipulate. This result can be explained by the small sample size. The median is only effective in eliminating outliers as long the underlying distribution of the individual contributions is approximately symmetric. Obviously, with three out of seven or eight values falsely reporting at the upper end of the range of contributions, this is not the case any more. Therefore, the median is not effective in mitigating manipulation effects in this case.[40] A similar effect can be observed for the trimmed mean, as well. Thus, this result demonstrates that, for a very small sample size, the effect of collusion cannot be efficiently mitigated by choosing a particular rate-setting procedure. In this case, the sample size needs to be increased so that, if a reasonable number of banks were to collude, it would still be a small subset of the whole sample. Thus, this result also highlights that for potential large-scale manipulations the validation of submissions using transaction data is of importance as alternative rate-setting procedures based on submissions cannot efficiently mitigate these effects.

In our sample, using the median does not change the final rate to a large extent.[41] However, a bank that can correctly guess the median rate might have a large impact with a relatively small change of its submission. For example, the median bank itself can achieve the maximum potential to manipulate by changing its submission by this amount. In contrast, in case of the trimmed mean, the submission must be manipulated to a larger extent.

[40] Note, that such a setup is comparable to the case of cartel-type manipulation as, e.g., in Frunza (2013).

[41] Note that this is in contrast to the findings of Market Participants Group on Reforming Interest Rate Benchmarks (2014) who conclude that, in the case of Euribor, the median results in lower rates and lower standard deviations.

5.4 Dynamic Alternative Rate Fixings

The static rate-setting methodologies only take the cross-section of the submissions on a given day into account, and hence ignore the pattern of submissions over time. In this section, we present *dynamic* alternative rate-fixing methodologies. Such methodologies use the time-series information of past submissions in addition to the present cross-section of submissions to detect outliers. Our analysis of the individual submissions shows a large amount of time-series noise in the data: the ranks of the individual submissions change frequently. Thus, dynamic outlier elimination can potentially be used to reduce this time-series noise. One reason for such noise could be that banks measure their own funding costs or credit risk with error.[42] On the other hand, it may be a tell-tale sign of manipulation, if a bank's submission on one day differs substantially from its submission on the previous day. Thus, the manipulation impact would also be captured by eliminating such large changes and dropping them from the computation of the trimmed mean (or other rate-fixing procedures). We implement such a dynamic methodology in conjunction with the current methodology using the trimmed mean, and also in conjunction with the best alternative static fixing, i.e., the median.[43]

We design the dynamic approach such that the total number, k, of excluded observations is at most equal to the number excluded in the trimming procedures currently used for Libor and Euribor, to maintain comparability. We exclude cross-sectional and time-series outliers in equal proportions. In most cases, this corresponds to exactly $k/2$ for each component and, thus, to an identical number of excluded outliers as in the static case. However, to avoid bias, we can only exclude an even number of observations when identifying cross-sectional outliers, as we have to trim the same number from the lower and upper ends. Thus, if $k/2$ is uneven, we consider $(k-1)/2$ cross-sectional outliers. We exclude the remaining outliers based on the absolute daily changes, i.e., considering the time-series; thus, the approach allows us to exactly determine the number of dynamic outliers, based on the specific number of total outliers, k.

When identifying the outliers for day t, we first exclude the defined number of outliers, based on absolute daily changes $c_{i,t}$ and, then, apply the cross-sectional filtering (using either the trimmed mean or the median). Thus, we rank the banks according to $c_{i,t}$:

[42] Note that, in certain periods, the funding situation of banks may indeed dramatically change. However, only transaction data would allow us to directly quantify such changes within the rate-setting procedure.

[43] We drop the use of the random-draw approach as it does not add any additional value.

$$c_{i,t} = |s_{i,t} - s_{i,t-1}| \tag{2}$$

In the presence of ties (i.e., banks with equal absolute changes $c_{i,t}$), we exclude only those outliers that are uniquely identified. Thus, in such cases, we eliminate less than k outliers overall. Although ties represent the same absolute change, the submissions are, most likely, not equal. Thus, it is not possible to exclude a fraction of these submissions, without potentially biasing the final fixing.[44] Figure 7 illustrates this approach and compares the static and dynamic trimming procedures.

Note that the approach we have presented here represents a first, simple example of how time-series information can be used in the rate-setting process using information from two successive days. Of course, many different alternatives exist, e.g., using the information on several past submissions, including the volatility of past submissions, or using a different number or sequence when identifying time-series outliers. However, our approach represents a very tractable algorithm that already provides very interesting results, as discussed below.

In our analysis, we use the same procedures as in the static cases to evaluate the effects of potential manipulation under the dynamic rate-setting procedures. In other words, we change the one, two or three lowest contributions by individual banks, setting them equal to the highest observed contribution, and then calculate the resulting (manipulated) benchmark rate and compare it to the original rate under the applied rate-setting procedure. Table 12 presents the manipulation effects of the dynamic approaches. Analyzing the results of the dynamic trimmed mean approach, the manipulation impact of one bank is 0.11 bp for Euribor, 0.24 bp for USD Libor and 0.79 bp for AUD Libor. Comparing these results to their static counterparts, we find that the dynamic approach leads to much lower effects, the static results being 0.17 bp for Euribor, 0.48 bp for USD Libor and 1.16 bp for AUD Libor. Interestingly, the dynamic median approach again performs better than the dynamic trimmed mean procedure, the results for one manipulating bank being 0.04 bp for Euribor, 0.17 bp for USD Libor and 0.55 bp for AUD Libor. We find similar results for the manipulation effects of two and three banks; for USD Libor, for example, having three manipulating banks has an impact of 0.73 bp for the

[44] It would be possible to randomly draw from the tied submissions, but we wish to refrain from incorporating a random selection issue into this mechanism. In principle, ties could also be broken using additional statistics (e.g., using differences from the mean), but this would make the calculation methodology even more complex.

trimmed mean approach, and 0.53 bp for the median approach.[45] Thus, similarly to the static cases, the median approach performs consistently and statistically significantly better than the alternatives. Again, the results show the importance of sample size. We also checked the impact of the dynamic median approach on the rate itself for the three month USD Libor. Changing the methodology to a dynamic mechanism has an impact on the Libor itself, with a mean difference of -0.02 bp and a standard deviation of 0.64 bp. Thus, a Libor calculated using the dynamic approach would have been slightly lower on average, with a moderate standard deviation.

Overall, the dynamic approaches perform better than the static ones. Interestingly, we find that the manipulation effects for the dynamic methodologies are reduced by up to 50%, relative to their static counterparts. In particular, combining time-series outlier elimination with the median of the remaining submissions results in the lowest manipulation potential overall.

The intuition behind the result that the dynamic methodology reduces the manipulation impact substantially can be explained as follows: In the case of the static trimmed mean methodology, only the highest and lowest submissions are dropped each day. The manipulation potential is, thus, determined by the trimmed range on that day. In other words, a bank that submits a very high submission (instead of a low one) is, of course, identified as an outlier, but the effect of the manipulation is that the submission just above the calculation window enters the trimmed range and the lowest submission in the window drops out. Thus, the impact corresponds to the full range of the calculation window. However, in the dynamic methodology, it is likely that the manipulated submission will be identified as a time-series outlier. In this case, a submission that would have been considered as a time-series outlier in the case of no manipulation enters the calculation window. This entering submission could be anywhere along the submission spectrum, and hence, on average, the effect of the manipulation corresponds to just half of the range. A trivial example of this effect is the following: If the "true" submission of the manipulating bank had already been excluded due to being a time-series outlier, then the manipulation attempt of the bank would not change the Libor rate in the dynamic approach in expectation, since the manipulated submission would again be an outlier in the cross-sectional trimming.

[45] Note that all these effects and differences are statistically significant at the 1 percent level.

Overall, we show, for the static and dynamic alternative rate-fixing procedures, that the panel size and the calculation method used to determine the final rate are important factors affecting the manipulation potential. A large panel size and the use of median rates, in combination with the elimination of outliers based on the time-series of submissions, can significantly reduce this potential. Note that the dynamic approach can be further adapted to specific needs by defining the length of the time-series used and, potentially, by incorporating the volatility of past submissions as a trimming criterion. Moreover, we find the possible impact of such a modification on Libor and Euribor to be much smaller compared to the reduction in the manipulation potential.

It is important to note here that a potential change in the calculation mechanism may lead to a new equilibrium and, thus, may change the behavior of banks when deciding on their submissions. In particular, calculation methods based on the time-series of submissions might increase the manipulation frequencies as a reaction to the decreasing effect of manipulation. For example, dynamic outlier detection might make it profitable to manipulate rates on consecutive days to avoid the possibility that a certain submission is eliminated because of its absolute change. However, this increased manipulation frequency could also increase the cost of manipulation as detection becomes more likely. As we do not model this cost structure and the possibility of detection, we do not evaluate the performance of the presented alternative measures along these lines.

5.5 Dynamic Rate Fixings Based on Multi-Day Windows

In addition to static and dynamic outlier detection methodologies, we also investigate how using a multi-day window to calculate the benchmark rate affects both the manipulation potential as well as the rate itself. For example, Duffie et al. (2013) analyze transaction data derived from Fed wire data and compare several sampling window sizes for USD Libor. They show that the volatility of the resulting rates is reduced when using longer calculation windows. However, they do not present the resulting new rates and, thus, do not directly compare these rates to the original rates, i.e., they do not explore the potential effects on the benchmark rate itself.

However, such an analysis is essential when analyzing rates based on multi-day windows, since using a moving average may have a strong impact on the final rate itself. Depending on the length of the window, the benchmark rates react differently to changing market conditions and, thus, could be significantly different from the rates calculated today. As for the effect of multi-day windows on the manipulation potential, it is likely that using an average rate calculated over a number of days would make it more difficult to manipulate the reference rate. On the one hand, because a single manipulation on one day would be averaged out to a certain degree and, on the other hand, since banks deciding to manipulate on multiple days to avoid this effect face an increasing risk of detection.

We implement a multi-day window approach for both the static and dynamic versions explained in Sections 5.3 and 5.4 for 3M USD Libor.[46] In the static cases, we perform the outlier detection for the individual days using the trimmed mean and median approaches and, then, calculate the average of the resulting single-day Libor rates for different window-lengths of one to five days.[47] Thus, the resulting rate corresponds to a moving average of the static approaches. (Note that a window of one day is equivalent to the static approaches presented in Section 5.3 and is presented to allow a direct comparison.) We implement the same methodology for the dynamic approach, i.e., we determine the dynamic outliers based on differences between consecutive days, as described in Section 5.4. Then, we calculate Libor as a moving average over the selected sampling window.

To calculate the manipulation potential, we use the approach that one bank manipulates the rate once within the sampling window.[48] Thus, based on the longest multi-day window of five days, we implicitly assume that the manipulation frequency of the relevant bank is once a week, at most. Note that if we allow manipulations on each day of the window, the trivial result of a multi-day approach is that it cannot reduce the manipulation potential. Thus, assuming a manipulation only once in the sampling window provides interesting results as the reported reduction in manipulation potential (see below) can be considered to be the *maximum* effect that would diminish linearly with higher manipulation frequencies. Furthermore, the information that was made public concerning the actual manipulation of the rates indicates that the manipulation most likely took place at low frequencies. However, we do not model

[46]Note that we do not report the results for AUD Libor and Euribor to conserve space. However, we find similar effects for theses rates.

[47]We also calculate the rates for longer time-windows and find the same patterns. However, the difference between the new and original rates would be much higher.

[48]Note that we do not present results for two and three banks manipulating the reference rate to conserve space. However, we find similar results compared to one bank.

the cost and risk of detection and, therefore, cannot derive optimal manipulation frequencies. In addition, we have to decide on the day of the manipulation within the multi-day window. Here, we assume that a bank can optimally time the manipulation. Thus, we change the lowest submission, making it equal to the highest submission on the day where such a change has the highest manipulation impact within the multi-day window.

We calculate the mean manipulation potential (including standard deviations) as well as the daily differences between the new reference rates and the original Libor rate based on the simple trimmed mean.[49] Table 13 shows the results of these approaches. As expect, we find significant reductions concerning the manipulation potential. Using the static trimmed mean approach based on a five day average reduces the manipulation potential from 0.48 bp to 0.11 bp. This potential reduces roughly in a linear fashion, when increasing the sampling window from one up to five days. The dynamic approach based on the median provides the lowest manipulation potential in the multi-day window setup, i.e., the potential reduces from 0.17 bp to 0.09 bp. It is interesting to note that the differences across the methods becomes smaller when increasing the number of days in the window. Thus, for five day windows, the difference between the static trimmed mean and the dynamic median approach is extremely small. Thus, the longer the window, the more the individual manipulation averages out, and the less important is the outlier elimination methodology. Thus, multi-day approaches are effective in reducing the manipulation potential, and a five day window provides very low potentials of around 0.1 bp across all methods.

However, we find that this decrease in the manipulation potential comes with a significant deviation from the original rates that may outweigh the positive effect of the reduction. The average of these deviations is close to zero across all methods, e.g., for the static trimmed mean approach based on five days the mean difference is 0.23 bp. Thus, the multi-day window approaches do not affect the level of the Libor rate. However, we find significant economic effects, when analyzing the standard deviation of these differences, e.g., again for the static trimmed mean approach, we find 1.48 bp for a two day window, and 4.67 bp for a five day window. The results are again similar across methods. As expected, the longer the window the slower is new information incorporated in the reference rate. Interestingly, we find when

[49] Obviously, the static approach using the trimmed mean based on a one day window is equivalent to the current mechanism yielding a difference of zero.

comparing the different methods that times-series outlier detection without multi-day windows provides similar reductions of the manipulation potential, without the negative effects on the resulting rates, compared to applying static approaches using multi-day sampling. Overall, we find that multi-day window approaches effectively reduce manipulation incentives assuming that manipulation frequencies do not increase due to detection risk. However, these approaches result in significant deviations from the original rates. As discussed in the previous section, incorporating the cost of detection and its feedback effect on manipulation strategies is beyond the scope of our paper.

6 Conclusion

Market reference interest rates such as Libor and Euribor, or their regional variants in Tokyo and other financial centers, play an important role in many financial contracts around the world. The integrity of these instruments, and of the markets themselves, depends crucially on the confidence that market participants place in the reliability and veracity of these rates. Unfortunately, developments in London and in other global financial centers have shaken this confidence, due to widespread allegations of manipulation in recent years. While prosecutors are currently engaged in taking action against the purported manipulators, regulators, including the Bank of England and the European Central Bank, are grappling with the issue of how to reform the rate-setting process, without creating too much confusion about the nature of the contracts or inducing potential litigation among contracting parties that use these rates as benchmarks in their contracts. We believe that our analysis provides useful additional findings for this reform.

In this paper, we quantify and explore the potential effects of the manipulation of Libor and Euribor, in detail. The focus of our study is on the analysis of the individual submissions of the panel banks for the calculations of the respective benchmark rates, for the time period January 2005 to December 2012. We present detailed results for 3M AUD Libor, 3M USD Libor and 3M Euribor, as representative examples. We report summarized results for all other currencies and tenors, which are in line with our conclusions regarding the detailed results. In our analysis, we explicitly take into account the possibility of collusion between several market participants. Furthermore, our setup allows us to quantify potential manipulation effects for the actual rate-setting process in place at present, and compare it to several alternative rate-fixing procedures. Moreover, we can directly analyze the effect on manipulation outcomes of the panel size and the underlying methodology used to elicit rate submissions from the banks.

Our results show that the cross-sectional volatility of individual submissions is high. Thus, actual manipulations may have used the full range within the observed submissions without risking immediate detection. In our main research question, we focus on the potential effects of such manipulations, quantifying the impact on the final fixing for different benchmark rates and rate-setting procedures, by considering simultaneous manipulation attempts by up to three banks. Overall, we find that the the calculation method and the panel size significantly influence the manipulation potential: the use of the median of the submissions (instead of the currently applied trimmed mean approach) and a large panel size substantially reduces the effect individual banks can have on the final rate. Furthermore, we show that using methodologies that eliminate outliers based on the time-series of submissions can reduce the manipulation potential even further. Moreover, we analyze the effects of these alternative methods on the level and volatility of the rate itself, and find the possible impact of such changes on Libor and Euribor to be rather small. In comparison, we find that using multi-day calculation windows mitigates the manipulation potential as well; however, such methods lead to significant deviations from the original rates. Table 14 summarizes the most important advantages and disadvantages of the analyzed approaches.

Although a change in the calculation methodology could be implemented fairly easily, increasing the panel size for Libor, in its current setup, could be more difficult. Given that banks are explicitly asked about their own funding rate for Libor, enlarging the sample might introduce even more heterogeneity, in terms of credit, liquidity, and outstanding positions, across the panel banks. Thus, increasing the sample size might only be feasible when asking about the money market funding costs of a (hypothetical) prime bank, as is done in the case of the Euribor.

There could potentially be other improvements made to the rate-setting process that have not been analyzed in this paper. One possibility is a mix of transactions and quote data, where the most liquid benchmark rates in terms of maturity and currency are set using actual transactions, and the spreads over these for the other currencies and maturities are set using quotes.

Such alternatives can be analyzed once a complete transaction data set is available. However, we find a clear need for an extensive transparency initiative that would make transaction reporting to a central database mandatory, as this would at least lead to the first step in validating individual rate submissions and, thus, might allow a data-driven identification of manipulation attempts.

A Robustness Checks (Internet Appendix)

A.1 Simulation Study of Manipulation Impact

In this appendix, we carry out a set of robustness checks using a simulation study. This setup enables us to present our results in a controlled environment without needing to allow for any strategic submissions by the panel banks. For that purpose, we model the distribution of individual contributions. This allows us to simulate the banks' submissions and analyze the properties of different rate-setting methodologies. In particular, we estimate the manipulation effects based on these simulated submissions and compare the results with the empirical data. Even more importantly, the simulation provides us with the opportunity to investigate how the manipulation impact changes if we apply our analyses to data that have already been manipulated (see Section A.2). This addresses an issue related to the use of the actual submissions, which may already be the result of manipulation.

We design the simulation study such that it resembles a representative case, by choosing to mimic the 3M USD Libor. Thus, in our simulation, 16 banks contribute to the final rate by submitting their individual submissions s_i (i.e., $n = 16$; this corresponds to the panel size of the 3M USD Libor during most of the sample period). In a first step, we analyze the empirical distribution of the banks' contributions to 3M USD Libor in our data set, so as to derive a suitable distribution function for the simulation study. For that purpose, we standardize the individual submissions observed on each day, t, as they show a strong time-dependence:

$$s_{i,t} = \frac{s_{i,t} - \hat{\mu}_t}{\hat{\sigma}_t} \tag{3}$$

where $\hat{\mu}_t$ and $\hat{\sigma}_t$ are the mean and standard deviation of the submissions on a given day, respectively. Figure 8 shows the distribution of these standardized submissions. Overall, we discover a symmetric distribution with fat tails. While this distribution does not strictly follow any given theoretical distribution, it can be reasonably approximated using a Student's t-distribution, with the degrees of freedom chosen such that the kurtosis is approximately equal to that of our estimated distribution.[50] The estimated kurtosis is 1.56, which corresponds to

[50]We tested different specifications, in particular the normal and log-normal distributions, but the results were basically identical.

approximately $df = 8$ degrees of freedom. Thus, for each simulated day we draw $n = 16$ submissions according to:

$$s_i \sim t(\mu, \sigma, df) \tag{4}$$

The set of n submissions will be denoted by $\mathbf{s}$. We are interested in the manipulation potential for the different rate-setting procedures analyzed in the prior sections. Therefore, we define manipulation as in the previous sections: Let m be the number of manipulating banks, then we set the m lowest submissions equal to the highest one. We denote the set of manipulated contributions as $\mathbf{s}^m$:

$$\mathbf{s}^m := \{s_{(i)}\}_{m<i\leq n} \cup_{i=1}^{m} \max(s_i, ..., s_n) \tag{5}$$

The function used to calculate the final fixing for each rate-setting methodology r is called f^r. The manipulation potential is thus calculated as

$$d^r = f^r(\mathbf{s}^m) - f^r(\mathbf{s}) \tag{6}$$

In particular, this setup allows us to compare the manipulation effects for different rate-setting procedures r. We calibrate the selected t-distribution such that it resembles an "average" day in our sample period. To this end, we take the mean of the historic average of the 3M USD Libor fixings during our sample period, given by $\mu = 235$ bp. We set the standard deviation equal to the average standard deviation of the daily submissions, i.e., $\sigma = 3.42$ bp. We estimate the manipulation impact for the untrimmed mean, trimmed mean and median (we do not present the random draw approach, as it basically provides the same impact as the trimmed mean), and we show the results obtained using three manipulating banks. We produce $20,000$ scenarios (i.e., the number of simulated days) in our simulation. Table 15 shows the parameters used for the simulation and the resulting manipulation potential.

The trimmed mean approach yields a simulated manipulation impact of 1.69 bp on average. This value corresponds well with the one observed empirically (i.e., 1.61 bp). The simulation confirms that the average manipulation impact is the highest when applying the untrimmed mean, at 2.02 bp, and that when applying the median is the lowest, at 1.51 bp. In addition,

Figure 9 shows the distribution of the simulated manipulation impact for the three rate-setting procedures, showing the variation in the manipulation effects over all scenarios. The distribution confirms the difference between the three rate-setting procedures; however, a certain degree of overlap between the distributions indicates that, for certain constellations of submissions, different rate-setting procedures could yield the lowest manipulation impact.

Overall, the simulation allows us to present results in a controlled environment, without any strategic submissions by the banks. The simulated manipulation effects are of the same order of magnitude as those in the data set and, thus, confirm the findings in the empirical part of our paper. The results are robust to changes in the basic setting, e.g., using different distributions or different numbers of banks.

A.2 Simulation Study Incorporating Pre-Manipulated Data

In this section, we use our simulation methodology to estimate the effect on our results of data that have already been manipulated. To this end, we manipulate the simulated data twice and estimate the distribution of the manipulated potential for the second manipulation attempt. Thus, we assume that we are analyzing the manipulation impact for a data set that already contains a certain proportion of manipulations.

For the first set of manipulations, we assume that three banks together manipulate their submissions on a fraction $p = 0.2$ of all days. This corresponds to a situation where, on average, three banks manipulate the rate once a week, and always in the same direction. We consider this a real stress test for our approach, as the information that was made public concerning the actual manipulation of the rates indicates that the manipulation took place at a much lower frequency and in different directions. In the second step, we consider these manipulated submissions as given, and use our approaches to estimate the manipulation impact of three banks.

All other parameters in the simulation study are identical to the setup presented in the previous section. The resulting averages of the manipulation potential are reported in Table 15. We find a manipulation potential of 1.92 bp for the untrimmed mean, 1.80 bp for the trimmed mean and 1.64 bp for the median. Thus, in this setup, the manipulation potential for the trimmed mean and median is slightly greater than in the case without any manipulated data;

however, we find the manipulation impact to be of the same order of magnitude as before. Furthermore, we still observe the same ranking when comparing different rate-setting procedures, with the application of the median approach resulting in the lowest impact.

Figure 10 shows the density estimates for the manipulation potential using the pre-manipulated submissions, providing further evidence that using underlying data containing a certain proportion of manipulated contributions does not change the overall nature of the resulting manipulation impact.

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Figures

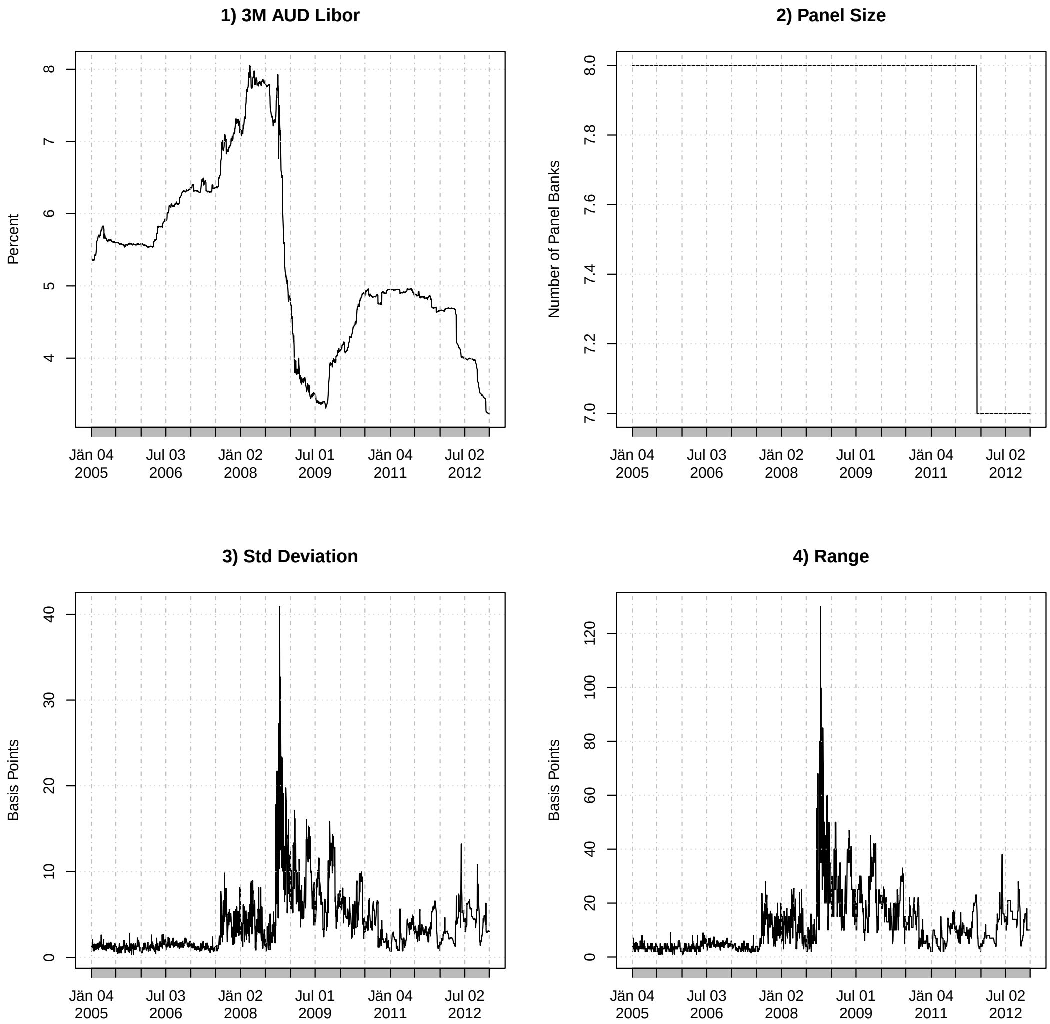

Figure 1. Descriptive statistics for the 3M AUD Libor

This figure shows the summary plots for the three month AUD Libor. Subfigure 1 shows the time-series of this reference rate. Subfigure 2 presents the panel size of banks contributing to the AUD Libor. Based on the individual contributions, subfigures 3 and 4 show the cross-sectional standard deviation and the range, i.e., the difference between the highest and the lowest contribution, on each day. Our data set contains the reference rate and the underlying contributions, obtained from Bloomberg for the time period from January 2005 to December 2012.

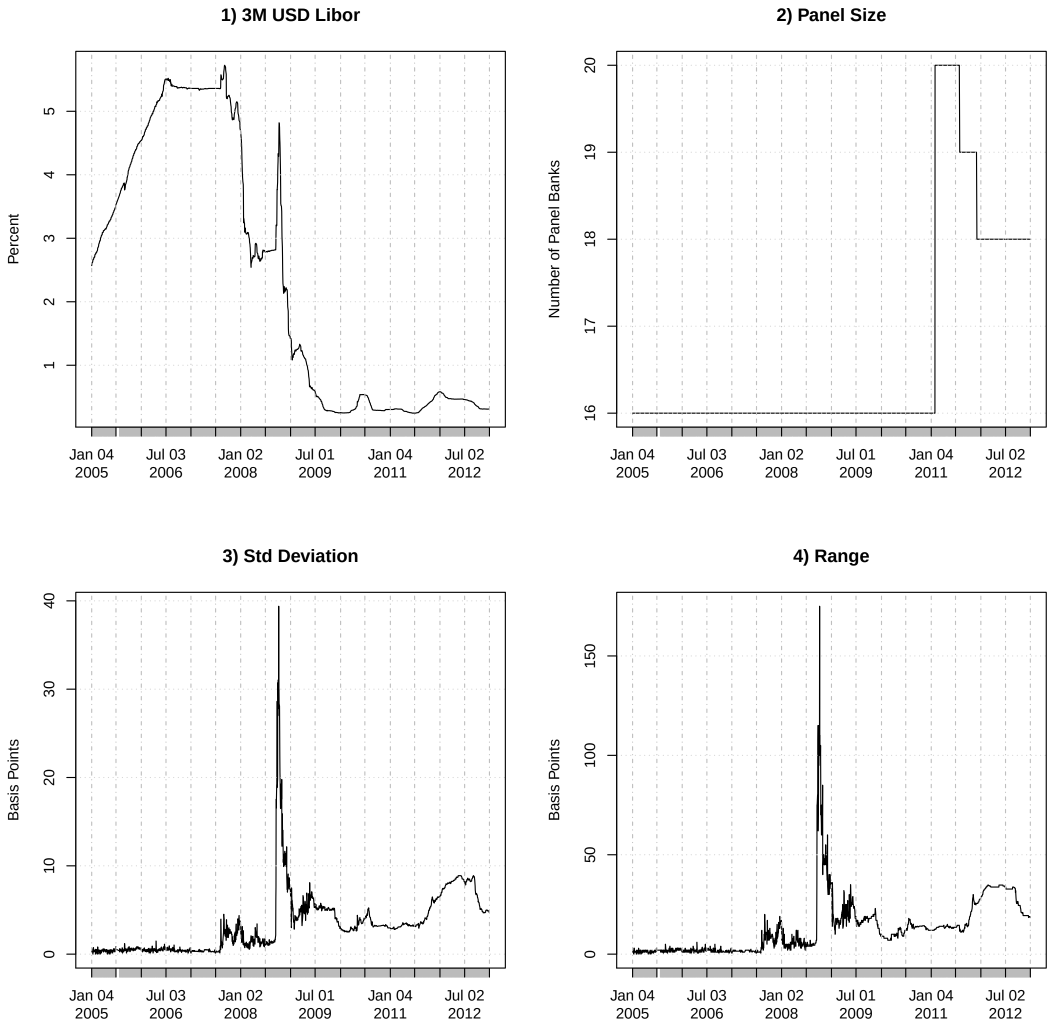

Figure 2. Descriptive statistics for the 3M USD Libor

This figure shows the summary plots for the three month USD Libor. Subfigure 1 shows the time-series of this reference rate. Subfigure 2 presents the panel size of banks contributing to the USD Libor. Based on the individual contributions, subfigures 3 and 4 show the cross-sectional standard deviation and the range, i.e., the difference between the highest and the lowest contribution, on each day. Our data set contains the reference rate and the underlying contributions, obtained from Bloomberg for the time period from January 2005 to December 2012.

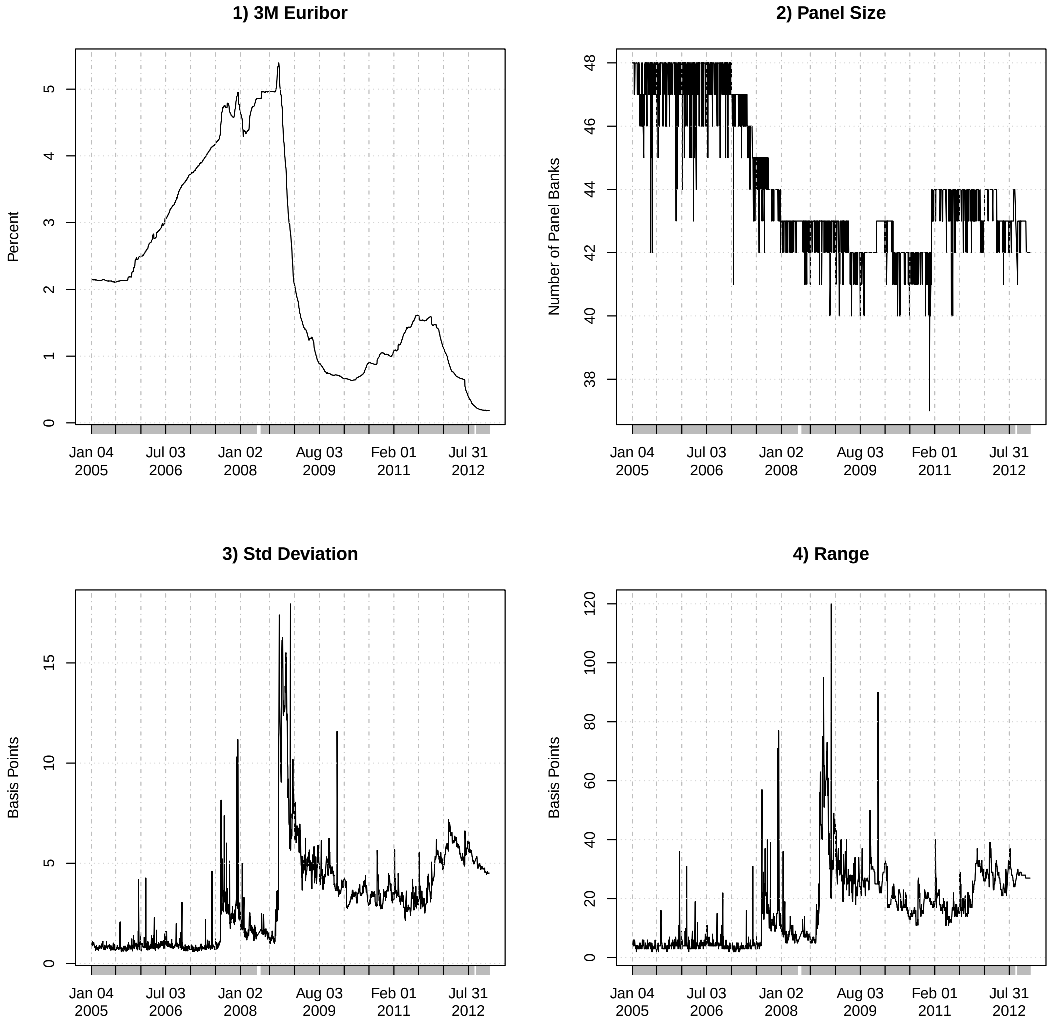

Figure 3. Descriptive statistics for the 3M Euribor

This figure shows the summary plots for the three month Euribor. Subfigure 1 shows the time-series of this reference rate. Subfigure 2 presents the panel size of banks contributing to the Euribor. Based on the individual contributions, subfigures 3 and 4 show the cross-sectional standard deviation and the range, i.e., the difference between the highest and the lowest contribution, on each day. Our data set contains the reference rate and the underlying contributions, obtained from the European Banking Federation for the time period from January 2005 to December 2012.

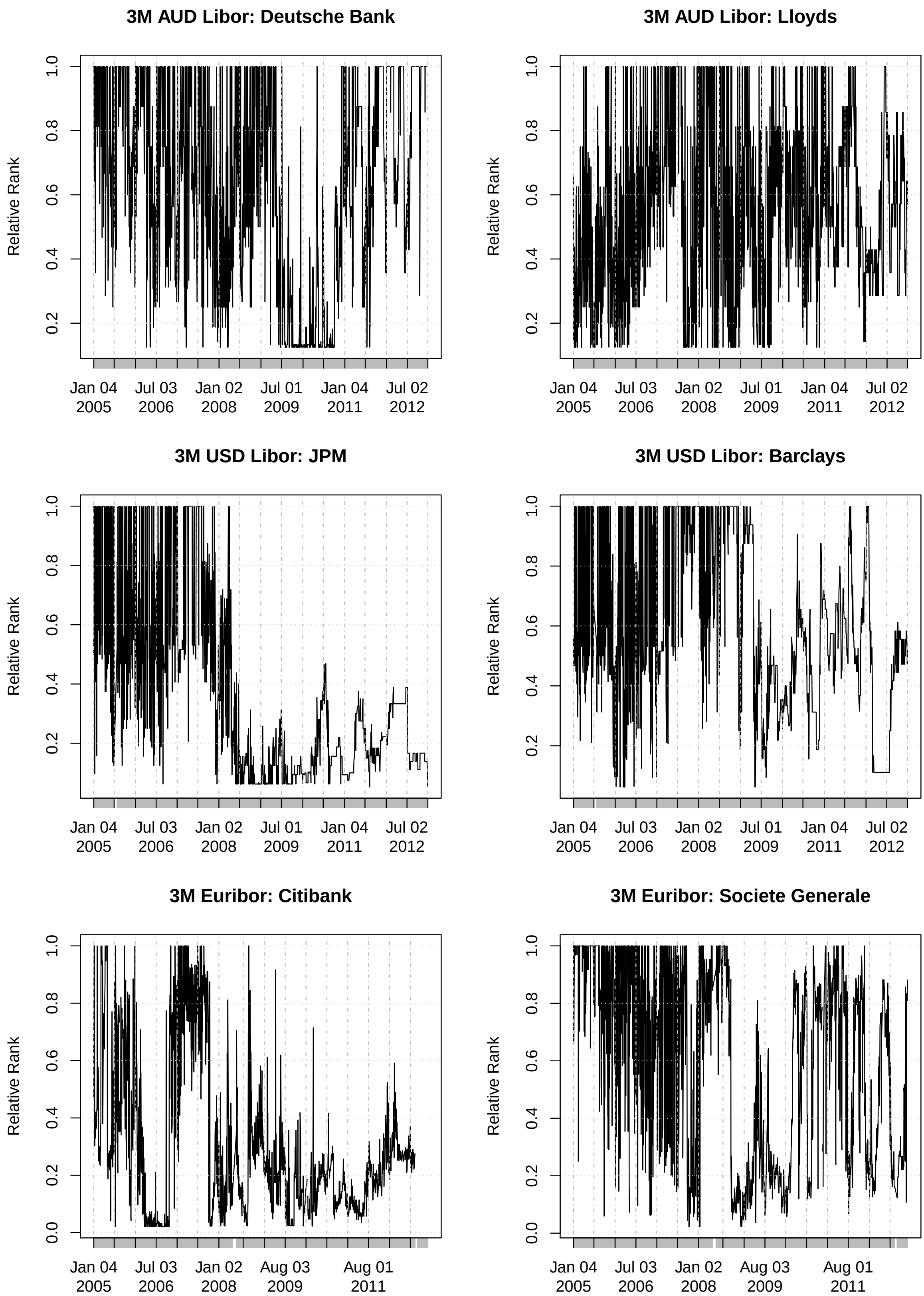

Figure 4. Ranks of panel banks' contributions

This figure shows the evolution of the ranks of selected panel banks' contributions for the three month AUD Libor, USD Libor and Euribor over time. To make the results comparable accross currencies, we standardize the ranks such that the bank with the highest rank (i.e., highest contribution) has a rank of 1. For each reference rate, we present the results for two representative panel banks. Our data set contains the reference rates and the underlying contributions, obtained from Bloomberg and the European Banking Federation for the time period from January 2005 to December 2012.

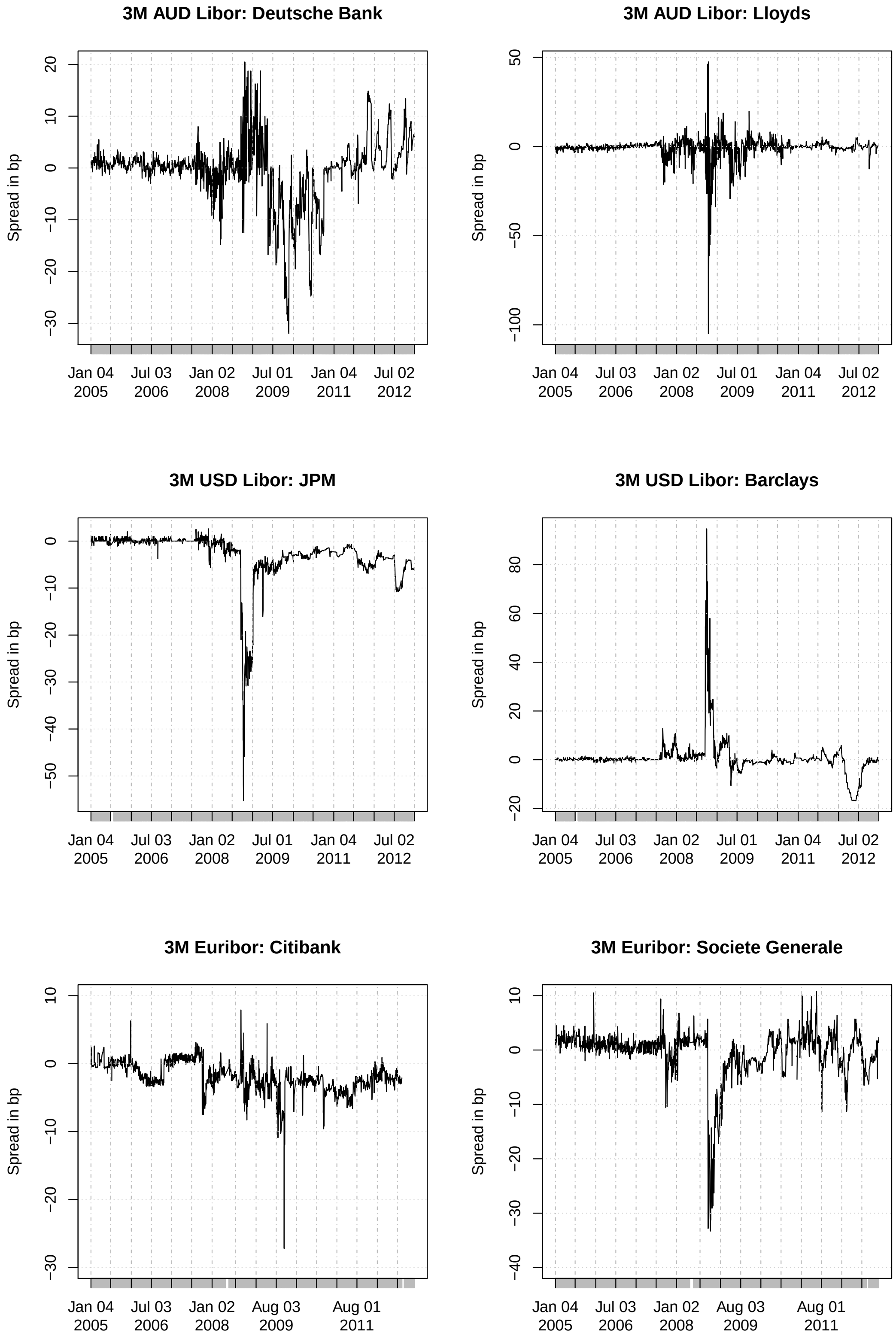

Figure 5. Difference between the final fixing and panel banks' contributions

This figure shows the difference between the individual contributions of selected panel banks and the final fixings for the three month AUD Libor, USD Libor and Euribor over time. For each reference rate, we present the results for two representative panel banks. Our data set contains the reference rates and the underlying contributions, obtained from Bloomberg and the European Banking Federation for the time period from January 2005 to December 2012.

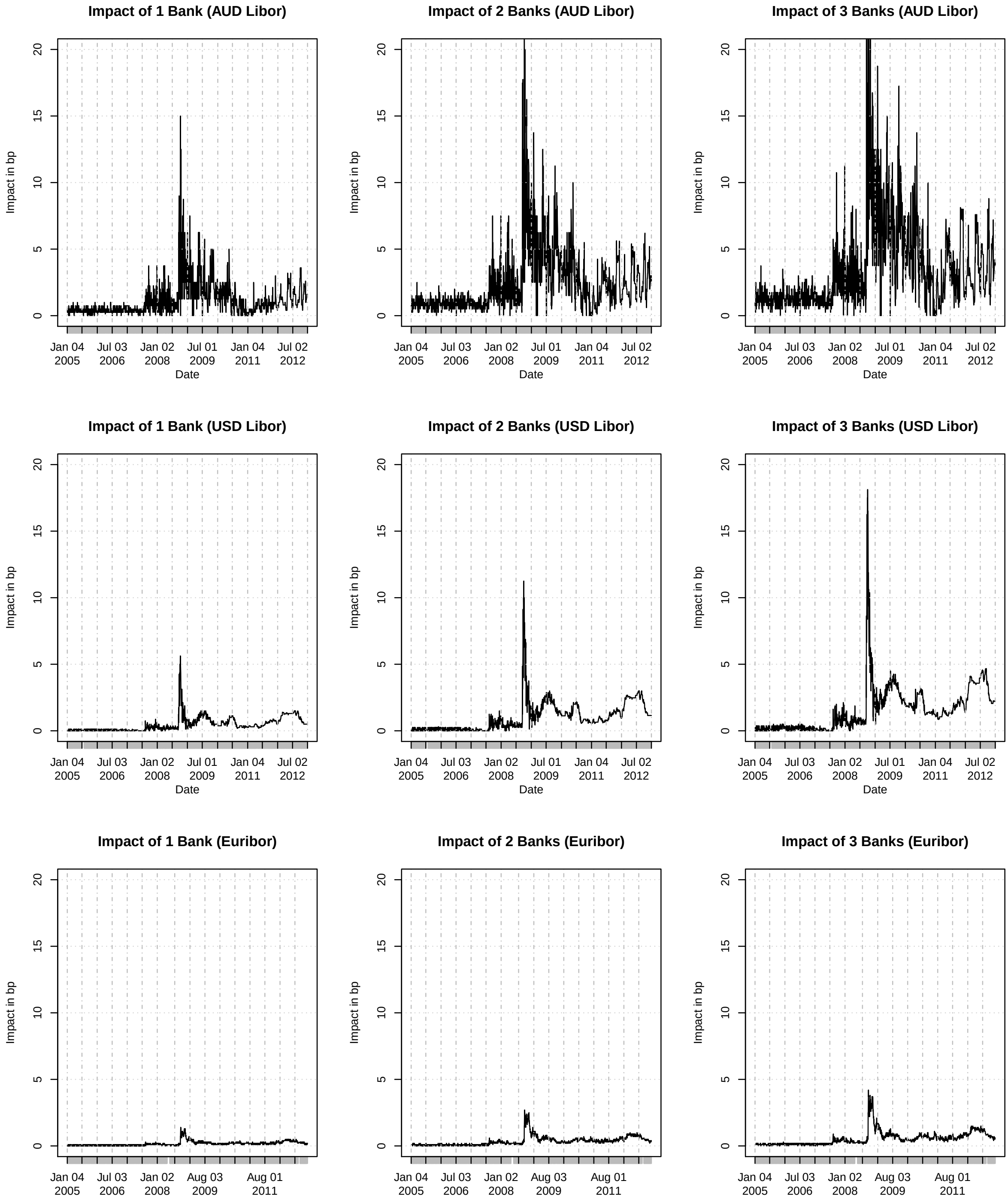

Figure 6. Potential manipulation effect

This figure shows the potential manipulation impact using the current rate-setting methodology for the three month AUD Libor, USD Libor and Euribor. For each day, we report the impact one, two or three colluding banks could have on the final fixing. We use the following approach to quantify these effects: We start out with the observed individual contributions made by the panel banks to the final rate. Then, we change the lowest observed contribution, making it equal to the highest observed contribution, for the case of a manipulation by one bank. The difference between the observed (historic) benchmark rate and the resulting benchmark rate after changing this one contribution is our measure of the potential effect of manipulation. We use the same approach when considering the manipulation potential for two or three banks, i.e., we set the lowest two (or three) contributions equal to the highest observed contribution. Our data set contains the reference rates and the underlying contributions, obtained from Bloomberg and the European Banking Federation for the time period from January 2005 to December 2012.

Figure 7. Dynamic trimming approach

This figure illustrates the concept of dynamic trimming for a hypothetical case with 8 banks. In the static approach, the 2 lowest and the 2 highest submissions are excluded as outliers. In the dynamic approach, we exclude two submissions based on the time-series (dark blue color) and subsequently two submissions based on the remaining cross-section (light red color). As time-series outliers, we exclude the submissions that show the highest absolute change from the previous day.

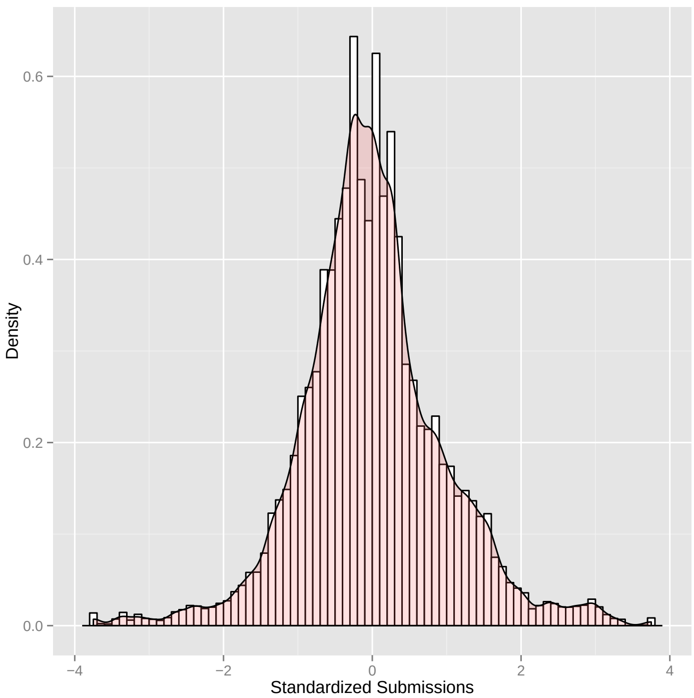

Figure 8. Distribution of standardized submissions for the 3M USD Libor

This figure shows the distribution of the standardized submissions made by panel banks to the three months USD Libor. We standardize the submissions using the mean and standard deviation of the individual contributions on each day. Our data set contains the reference rates and the underlying contributions, obtained from Bloomberg for the time period from January 2005 to December 2012.

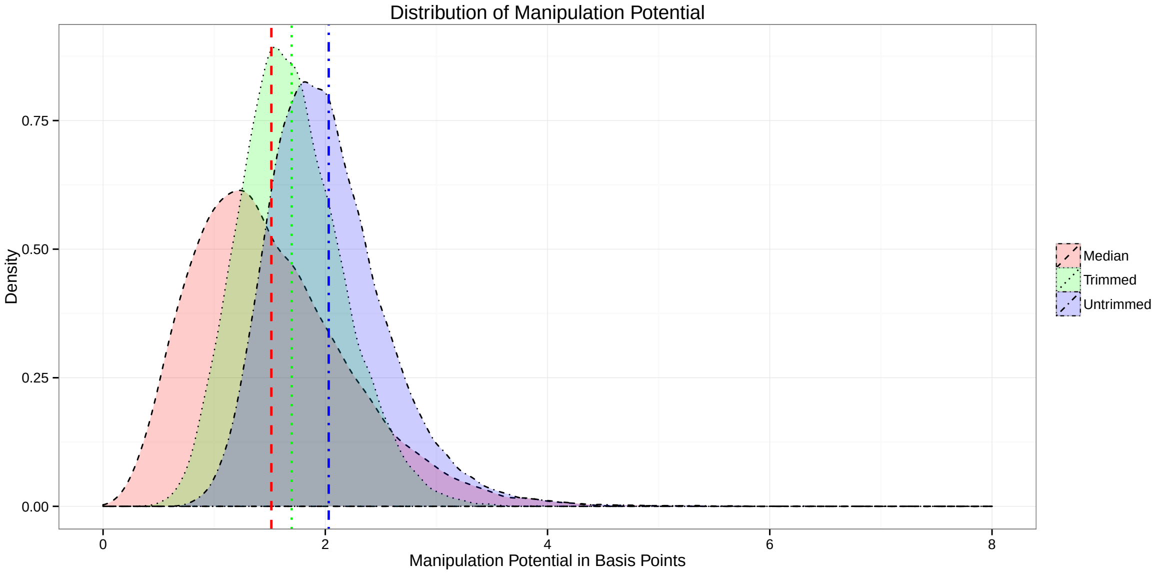

Figure 9. Simulated manipulation potential

This figure shows the distribution of the simulated manipulation potential for the trimmed mean, untrimmed mean and median. The vertical lines indicate the average of the manipulation potential. We simulate 20,000 runs for a panel that is calibrated to the three month USD Libor. In each run, we simulate 16 submissions using a t-distribution. We match the mean and standard deviation to the observed Libor rate submissions during the sample period. We calibrate the degrees of freedom to the average kurtosis. The manipulation potential based on three colluding banks is provided for each run: We start out with the simulated contributions made by the panel banks to the final rate. Then, we change the three lowest observed contributions, making them equal to the highest contribution. The difference between the final rates with and without manipulation is our measure of the potential effect of manipulation.

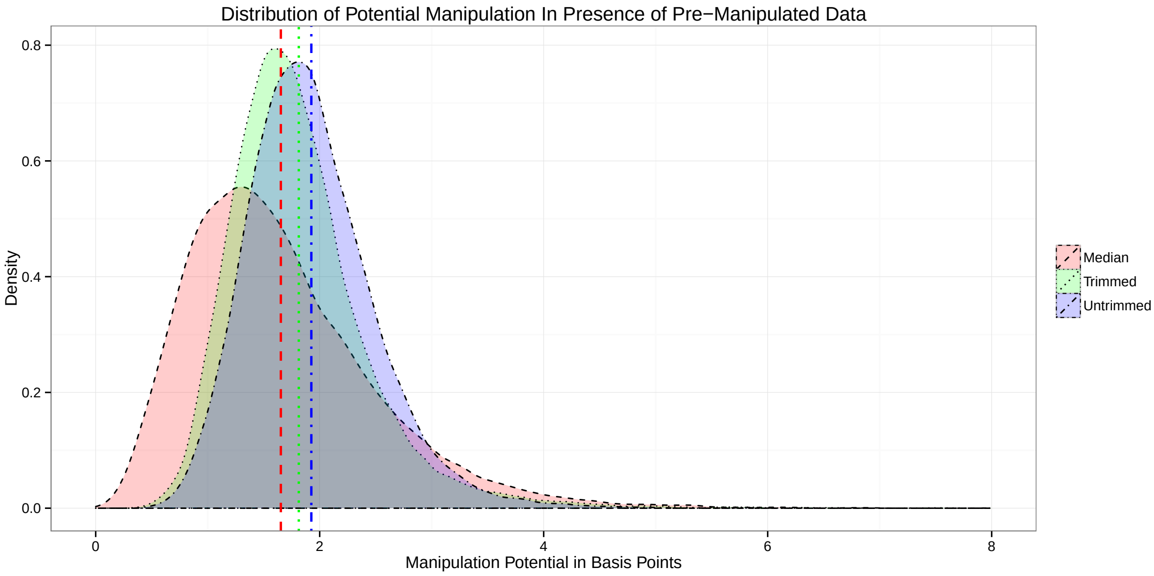

Figure 10. Simulated manipulation potential based on pre-manipulated data

This figure shows the distribution of manipulation potential where we simulate pre-manipulated data, representing a robustness check as the observed empirical data may contain a certain degree of manipulation as well. The vertical lines show the average of the manipulation potential. We simulate $20,000$ runs for a panel that is calibrated to the three month USD Libor. In each run, we simulate 16 submissions using a t-distribution. We match the mean and standard deviation to the observed Libor rate submissions during the sample period. We calibrate the degrees of freedom to the average kurtosis. We assume that on a fraction of 0.2 of all days three banks manipulate the rate up. We then consider these manipulated submissions as given and we change the three lowest observed contributions, making them equal to the highest contribution. The difference between the final rates with and without this second manipulation is our measure of the manipulation potential in each run.

Tables

Table 1. Trimming approach for the Libor panel

This table shows the number of excluded bank submissions on each side of the Libor panel given the selected panel size. In principle, the highest and lowest 25% of all submissions are excluded. However, a particular rounding approach is applied for non-integer numbers. For example for a panel of size 7, the highest and lowest contributions are excluded, although 25% of the panel represents 1.75 contributions. This approach ensures that not more than 55% of the submissions are removed.

Panel size	Nr. of excluded banks
6 - 7	1
8 - 10	2
11 - 14	3
15 - 18	4
19 - 20	5

Table 2. Trimming approach for the Euribor panel

This table shows the number of excluded bank submissions on each side of the Euribor panel given the selected panel size. In principle, the highest and lowest 15% of all submissions are excluded. The common method of rounding is applied to non-integer numbers. For example, for a panel of size 18, the three highest and three lowest contributions are excluded.

Panel size	Nr. of excluded banks
12 - 16	2
17 - 23	3
24 - 29	4
30 - 36	5
37 - 43	6
44 - 45	7

Table 3. Effect on 3M AUD Libor rate when changing lowest submission

This table shows the calculation of the three month AUD Libor rate on December 31, 2012. On this day the AUD Libor panel consisted of 7 banks. Thus, the highest and lowest contributions were removed in the trimming process. The first row shows the actual contributions on that day. The contributions of banks 2–6 are used to calculate the Libor rate, yielding a final fixing of 3.238%. In the second row, we illustrate the effect on this rate if a single contribution were different (e.g., because of manipulation). If the bank with the lowest contribution (Bank 1) had instead submitted a contribution equal to that of the bank with the highest contribution (Bank 7), the fixing on that day would then be the average of the contributions of banks 3–7, i.e., the calculation window would shift by one bank. In this case, the final fixing would be 3.252%, an increase of 1.4 bp.

Bank 1	Bank 2	Bank 3	Bank 4	Bank 5	Bank 6	Bank 7	Bank 1
3.20	3.23	3.23	3.24	3.24	3.25	3.30	
	3.23	3.23	3.24	3.24	3.25	3.30	3.30

Table 4. Frequencies of banks falling within or outside of the calculation panel for 3M AUD Libor

This table shows the frequencies with which each panel bank fell within or outside of (below/above) the subset used to calculate the three month AUD Libor. As the cross-sectional standard deviation of the contributions was very low before the onset of the financial crisis, we report our results for the full time period, the time period before the financial crisis (January 2005 to June 2007) and the time period of the financial crisis from July 2007 onwards. The first three columns show the frequencies with which the banks were in the panel used to calculate the trimmed mean. Tied contributions were assigned proportionately here. The columns labeled *below Panel* and *above Panel* show the percentage of days on which a bank's contribution was strictly below and above this panel, respectively. Our data set contains the reference rate and the underlying contributions, obtained from Bloomberg for the time period from January 2005 to December 2012.

	in Panel			**below Panel**			**above Panel**		
Bank	Jan 2005 Dec 2012	Jan 2005 Jun 2007	Jul 2007 Dec 2012	Jan 2005 Dec 2012	Jan 2005 Jun 2007	Jul 2007 Dec 2012	Jan 2005 Dec 2012	Jan 2005 Jun 2007	Jul 2007 Dec 2012
Barclays	0.56	0.71	0.53	0.11	0.09	0.11	0.20	0.05	0.23
CommonwealthBank	0.63	0.42	0.73	0.20	0.37	0.12	0.09	0.07	0.09
Deutsche	0.44	0.48	0.42	0.19	0.08	0.25	0.26	0.30	0.25
HBOS	0.44	0.39	0.51	0.05	0.06	0.03	0.37	0.41	0.32
HSBC	0.85		0.85	0.11		0.11	0.00		0.00
JPM	0.50	0.63	0.46	0.27	0.07	0.34	0.11	0.12	0.11
Lloyds	0.60	0.56	0.62	0.15	0.17	0.14	0.13	0.12	0.14
NationalAustralia	0.52	0.72	0.41	0.28	0.06	0.41	0.09	0.04	0.11
RBS	0.52	0.47	0.54	0.06	0.05	0.07	0.29	0.33	0.28
UBS	0.41	0.29	0.47	0.39	0.59	0.27	0.18	0.12	0.21

Table 5. Frequencies of banks falling within or outside of the calculation panel for 3M USD Libor

This table shows the frequencies with which each panel bank fell within or outside of (below/above) the subset used to calculate the three month USD Libor. As the cross-sectional standard deviation of the contributions was very low before the onset of the financial crisis, we report our results for the full time period, the time period before the financial crisis (January 2005 to June 2007) and the time period of the financial crisis from July 2007 onwards. The first three columns show the frequencies with which the banks were in the panel used to calculate the trimmed mean. Tied contributions were assigned proportionately here. The columns labeled *below Panel* and *above Panel* show the percentage of days on which a bank's contribution was strictly below and above this panel, respectively. Our data set contains the reference rate and the underlying contributions, obtained from Bloomberg for the time period from January 2005 to December 2012.

Bank	**in Panel**			**below Panel**			**above Panel**		
	Jan 2005 Dec 2012	Jan 2005 Jun 2007	Jul 2007 Dec 2012	Jan 2005 Dec 2012	Jan 2005 Jun 2007	Jul 2007 Dec 2012	Jan 2005 Dec 2012	Jan 2005 Jun 2007	Jul 2007 Dec 2012
AbbeyNational	0.54	0.54		0.03	0.03		0.02	0.02	
BankOfNovaScotia	0.84		0.84	0.13		0.13	0.00		0.00
BankOfTokyo	0.43	0.40	0.44	0.05	0.15	0.01	0.43	0.28	0.50
Barclays	0.53	0.47	0.55	0.12	0.10	0.12	0.22	0.16	0.25
BNPParibas	0.41		0.41	0.00		0.00	0.51		0.51
BoA	0.59	0.32	0.70	0.22	0.30	0.18	0.15	0.42	0.04
CACIB	0.10		0.10	0.00		0.00	0.88		0.88
Citibank	0.64	0.62	0.65	0.19	0.06	0.25	0.03	0.06	0.02
CSFB	0.61	0.63	0.61	0.11	0.04	0.13	0.14	0.05	0.18
DeutscheBank	0.42	0.42	0.42	0.40	0.31	0.43	0.14	0.31	0.06
HBOS	0.61	0.59	0.64	0.03	0.03	0.03	0.10	0.04	0.20
HSBC	0.32	0.53	0.22	0.52	0.10	0.70	0.03	0.06	0.02
JPM	0.33	0.50	0.25	0.49	0.08	0.68	0.04	0.12	0.01
Lloyds	0.75	0.57	0.83	0.07	0.05	0.08	0.03	0.03	0.03
Norinchukin	0.33	0.32	0.33	0.10	0.28	0.02	0.55	0.40	0.61
Rabobank	0.55	0.55	0.55	0.30	0.10	0.38	0.05	0.10	0.02
RBC	0.81	0.60	0.89	0.05	0.10	0.03	0.06	0.09	0.05
RBS	0.31	0.31	0.31	0.23	0.44	0.13	0.44	0.32	0.49
SocGen	0.49		0.49	0.05		0.05	0.42		0.42
Sumitomo	0.72		0.72	0.00		0.00	0.23		0.23
UBS	0.54	0.58	0.53	0.27	0.12	0.34	0.11	0.12	0.10
WestLB	0.45	0.60	0.36	0.02	0.05	0.01	0.37	0.04	0.57

Table 6. Frequencies of banks falling within or outside of the calculation panel for 3M Euribor

This table shows the frequencies with which each panel bank fell within or outside of (below/above) the subset used to calculate the three month Euribor. As the cross-sectional standard deviation of the contributions was very low before the onset of the financial crisis, we report our results for the full time period, the time period before the financial crisis (January 2005 to June 2007) and the time period of the financial crisis from July 2007 onwards. The first three columns show the frequencies with which the banks were in the panel used to calculate the trimmed mean. Tied contributions were assigned proportionately here. The columns labeled *below Panel* and *above Panel* show the percentage of days on which a bank's contribution was strictly below and above this panel, respectively. Our data set contains the reference rate and the underlying contributions, obtained from the European Banking Federation for the time period from January 2005 to December 2012.

	in Panel			**below Panel**			**above Panel**		
Bank	Jan 2005 Dec 2012	Jan 2005 Jun 2007	Jul 2007 Dec 2012	Jan 2005 Dec 2012	Jan 2005 Jun 2007	Jul 2007 Dec 2012	Jan 2005 Dec 2012	Jan 2005 Jun 2007	Jul 2007 Dec 2012
ABN Amro	0.68	0.73	0.62	0.07	0.05	0.09	0.14	0.06	0.22
AIB Group	0.50	0.79	0.37	0.01	0.03	0.00	0.39	0.02	0.55
Banca Intesa	0.87	0.80	0.90	0.02	0.01	0.02	0.01	0.01	0.01
Banca MPS	0.86	0.70	0.94	0.03	0.07	0.01	0.06	0.12	0.03
Banco Bilbao	0.47	0.13	0.62	0.24	0.53	0.12	0.38	0.73	0.22
Banco Santander	0.77	0.79	0.76	0.06	0.05	0.07	0.08	0.03	0.10
Bank of Ireland	0.87	0.77	0.92	0.03	0.05	0.02	0.03	0.04	0.02
Bank of Tokyo Mitsubishi	0.49	0.31	0.57	0.38	0.38	0.38	0.17	0.52	0.00
Banque Postale	0.62		0.62	0.19		0.19	0.15		0.15
Barclays	0.71	0.78	0.68	0.16	0.06	0.20	0.06	0.05	0.07
Bayern LB	0.63	0.43	0.73	0.24	0.39	0.17	0.12	0.28	0.05
BCEE	0.84	0.81	0.86	0.07	0.01	0.10	0.01	0.01	0.00
Belfius	0.63	0.77	0.55	0.02	0.01	0.02	0.25	0.02	0.38
BNL	0.76	0.76		0.06	0.06		0.05	0.05	
BNP Paribas	0.50	0.57	0.47	0.33	0.27	0.35	0.12	0.17	0.10
Capita	0.87	0.87	0.90	0.00	0.00	0.00	0.00	0.00	0.02
Cecabank	0.59	0.74	0.52	0.08	0.06	0.08	0.23	0.07	0.31
Cecabank	0.00		0.00	0.00		0.00	0.00		0.00
CGD	0.64	0.80	0.57	0.01	0.01	0.01	0.26	0.01	0.38
CIC	0.59	0.59	0.58	0.20	0.18	0.21	0.14	0.19	0.12
Citibank	0.56	0.50	0.58	0.33	0.33	0.33	0.07	0.21	0.01
Commerzbank	0.87	0.67	0.96	0.06	0.15	0.01	0.03	0.09	0.01
Credite Agricole CIB	0.69	0.80	0.64	0.16	0.01	0.23	0.05	0.02	0.06
Danske Bank	0.81	0.79	0.82	0.06	0.01	0.09	0.04	0.01	0.05
Deka Bank	0.07		0.07	0.00		0.00	0.84		0.84
Deutsche Bank	0.39	0.42	0.38	0.40	0.40	0.39	0.23	0.32	0.18
Dexia	0.71		0.71	0.09		0.09	0.17		0.17
Dresdner Bank	0.83	0.77	0.92	0.02	0.03	0.01	0.02	0.01	0.02
DZ Bank	0.58	0.75	0.50	0.20	0.07	0.25	0.14	0.07	0.16
Erste Bank	0.43	0.73	0.29	0.02	0.07	0.00	0.45	0.09	0.62
Fortis	0.63	0.55	0.70	0.11	0.19	0.03	0.25	0.27	0.22
HSBC	0.67	0.68	0.67	0.20	0.11	0.24	0.08	0.16	0.05
HVB	0.78	0.78		0.06	0.06		0.05	0.05	
ING	0.86	0.77	0.90	0.04	0.05	0.04	0.04	0.06	0.03
JPM	0.52	0.72	0.44	0.35	0.06	0.49	0.03	0.08	0.00
KBC	0.80	0.82	0.79	0.02	0.03	0.01	0.11	0.02	0.15
la Caixa	0.97		0.97	0.00		0.00	0.01		0.01
LB Baden-Württemberg	0.79	0.71	0.82	0.08	0.10	0.08	0.05	0.06	0.05
LB Berlin	0.90	0.81	0.95	0.02	0.04	0.01	0.02	0.02	0.01
LB Hessen-Thüringen	0.78	0.80	0.76	0.01	0.03	0.00	0.12	0.03	0.16
Natexis	0.69	0.71	0.61	0.09	0.08	0.13	0.11	0.09	0.19
National Bank of Greece	0.84	0.82	0.85	0.01	0.01	0.00	0.07	0.02	0.09
Natixis	0.69	0.62	0.72	0.09	0.18	0.05	0.17	0.17	0.17
Nordea	0.93	0.80	0.99	0.00	0.01	0.00	0.00	0.01	0.00
Nord LB	0.73	0.72	0.74	0.12	0.11	0.12	0.08	0.09	0.07
Pohjola	0.96		0.96	0.03		0.03	0.00		0.00
Rabobank	0.60	0.77	0.52	0.31	0.03	0.43	0.01	0.02	0.01
RBI	0.82	0.80	0.84	0.07	0.00	0.10	0.01	0.00	0.01
RBS	0.84		0.84	0.09		0.09	0.05		0.05
Sanpaolo IMI	0.90	0.90		0.00	0.00		0.00	0.00	
Societe Generale	0.58	0.43	0.64	0.18	0.29	0.13	0.22	0.40	0.13
Svenska	0.90	0.82	0.93	0.01	0.02	0.00	0.03	0.02	0.03
UBI Banca	1.00		1.00	0.00		0.00	0.00		0.00
UBS	0.56	0.73	0.48	0.21	0.08	0.27	0.16	0.05	0.20
Unicredit	0.88	0.80	0.91	0.03	0.02	0.04	0.02	0.02	0.02
West LB	0.77	0.70	0.81	0.04	0.10	0.01	0.12	0.09	0.13

Table 7. Rank changes of banks for 3M AUD Libor

This table shows the mean and standard deviation of the daily absolute rank changes for the panel banks contributing to the three month AUD Libor. As the cross-sectional standard deviation of the contributions was very low before the onset of the financial crisis, we report our results for the full time period, the time period before the financial crisis (January 2005 to June 2007) and the time period of the financial crisis from July 2007 onwards. To make the results comparable across currencies, we standardize the ranks such that the bank with the highest rank (i.e., highest contribution) has a rank of 1. For example, a rank change of 0.25 means that a bank's rank change corresponds to a quarter of the panel. Our data set contains the reference rate and the underlying contributions, obtained from Bloomberg for the time period from January 2005 to December 2012.

	Mean			**StdDev**		
Bank	Jan 2005 Dec 2012	Jan 2005 Jun 2007	Jul 2007 Dec 2012	Jan 2005 Dec 2012	Jan 2005 Jun 2007	Jul 2007 Dec 2012
Barclays	0.13	0.20	0.12	0.16	0.16	0.16
CommonwealthBank	0.17	0.15	0.18	0.17	0.15	0.18
Deutsche	0.11	0.13	0.10	0.14	0.14	0.14
HBOS	0.18	0.18	0.19	0.18	0.19	0.17
HSBC	0.07		0.07	0.10		0.10
JPM	0.11	0.20	0.08	0.16	0.18	0.13
Lloyds	0.16	0.18	0.14	0.18	0.17	0.18
NationalAustralia	0.15	0.18	0.13	0.16	0.15	0.17
RBS	0.13	0.16	0.12	0.16	0.16	0.16
UBS	0.12	0.10	0.13	0.16	0.13	0.17

Table 8. Rank changes of banks for 3M USD Libor

This table shows the mean and standard deviation of the daily absolute rank changes for the panel banks contributing to the three month USD Libor. As the cross-sectional standard deviation of the contributions was very low before the onset of the financial crisis, we report our results for the full time period, the time period before the financial crisis (January 2005 to June 2007) and the time period of the financial crisis from July 2007 onwards. To make the results comparable across currencies, we standardize the ranks such that the bank with the highest rank (i.e., highest contribution) has a rank of 1. For example, a rank change of 0.25 means that a bank's rank change corresponds to a quarter of the panel. Our data set contains the reference rate and the underlying contributions, obtained from Bloomberg for the time period from January 2005 to December 2012.

	Mean			**StdDev**		
Bank	Jan 2005 Dec 2012	Jan 2005 Jun 2007	Jul 2007 Dec 2012	Jan 2005 Dec 2012	Jan 2005 Jun 2007	Jul 2007 Dec 2012
AbbeyNational	0.27	0.27		0.26	0.26	
BankOfNovaScotia	0.02		0.02	0.03		0.03
BankOfTokyo	0.08	0.18	0.04	0.15	0.22	0.08
Barclays	0.10	0.21	0.05	0.16	0.22	0.09
BNPParibas	0.01		0.01	0.03		0.03
BoA	0.11	0.21	0.06	0.19	0.26	0.12
CACIB	0.01		0.01	0.02		0.02
Citibank	0.09	0.18	0.05	0.14	0.19	0.09
CSFB	0.10	0.18	0.07	0.15	0.19	0.11
DeutscheBank	0.11	0.20	0.07	0.18	0.22	0.13
HBOS	0.19	0.21	0.15	0.19	0.21	0.15
HSBC	0.10	0.20	0.05	0.17	0.23	0.10
JPM	0.09	0.21	0.04	0.16	0.23	0.08
Lloyds	0.10	0.20	0.06	0.16	0.21	0.10
Norinchukin	0.08	0.17	0.04	0.15	0.21	0.09
Rabobank	0.11	0.21	0.07	0.17	0.22	0.13
RBC	0.10	0.20	0.06	0.15	0.20	0.10
RBS	0.09	0.16	0.06	0.16	0.20	0.12
SocGen	0.02		0.02	0.05		0.05
Sumitomo	0.01		0.01	0.02		0.02
UBS	0.10	0.21	0.05	0.16	0.21	0.10
WestLB	0.11	0.19	0.06	0.16	0.20	0.11

Table 9. Rank changes of banks for 3M Euribor

This table shows the mean and standard deviation of the daily absolute rank changes for the panel banks contributing to the three month Euribor. As the cross-sectional standard deviation of the contributions was very low before the onset of the financial crisis, we report our results for the full time period, the time period before the financial crisis (January 2005 to June 2007) and the time period of the financial crisis from July 2007 onwards. To make the results comparable across currencies, we standardize the ranks such that the bank with the highest rank (i.e., highest contribution) has a rank of 1. For example, a rank change of 0.25 means that a bank's rank change corresponds to a quarter of the panel. Our data set contains the reference rate and the underlying contributions, obtained from the European Banking Federation for the time period from January 2005 to December 2012.

Bank	Mean			StdDev		
	Jan 2005 Dec 2012	Jan 2005 Jun 2007	Jul 2007 Dec 2012	Jan 2005 Dec 2012	Jan 2005 Jun 2007	Jul 2007 Dec 2012
ABN Amro	0.13	0.14	0.13	0.16	0.16	0.17
AIB Group	0.11	0.20	0.06	0.15	0.18	0.12
Banca Intesa	0.09	0.14	0.06	0.10	0.14	0.07
Banca MPS	0.12	0.15	0.11	0.13	0.15	0.12
Banco Bilbao	0.06	0.05	0.07	0.11	0.11	0.10
Banco Santander	0.10	0.16	0.08	0.13	0.16	0.11
Bank of Ireland	0.11	0.15	0.09	0.12	0.14	0.10
Bank of Tokyo Mitsubishi	0.06	0.08	0.05	0.09	0.10	0.08
Banque Postale	0.11		0.11	0.14		0.14
Barclays	0.11	0.18	0.08	0.14	0.16	0.11
Bayern LB	0.13	0.14	0.12	0.15	0.15	0.14
BCEE	0.09	0.14	0.07	0.12	0.14	0.10
Belfius	0.09	0.12	0.07	0.12	0.12	0.11
BNL	0.15	0.15		0.15	0.15	
BNP Paribas	0.10	0.16	0.07	0.15	0.19	0.12
Capita	0.17	0.16	0.19	0.15	0.15	0.16
Cecabank	0.10	0.17	0.07	0.13	0.16	0.10
Cecabank	0.00		0.00	0.00		0.00
CGD	0.07	0.10	0.05	0.09	0.09	0.08
CIC	0.10	0.15	0.08	0.15	0.17	0.13
Citibank	0.07	0.11	0.05	0.11	0.14	0.09
Commerzbank	0.13	0.22	0.09	0.15	0.20	0.10
Credite Agricole CIB	0.11	0.15	0.09	0.14	0.14	0.13
Danske Bank	0.11	0.10	0.11	0.14	0.09	0.16
Deka Bank	0.01		0.01	0.01		0.01
Deutsche Bank	0.07	0.14	0.05	0.13	0.16	0.10
Dexia	0.11		0.11	0.15		0.15
Dresdner Bank	0.12	0.12	0.10	0.11	0.12	0.10
DZ Bank	0.14	0.22	0.10	0.17	0.20	0.14
Erste Bank	0.09	0.16	0.06	0.14	0.16	0.11
Fortis	0.16	0.17	0.15	0.18	0.17	0.19
HSBC	0.10	0.16	0.07	0.13	0.16	0.11
HVB	0.12	0.12		0.12	0.12	
ING	0.11	0.17	0.09	0.14	0.16	0.12
JPM	0.08	0.15	0.05	0.12	0.15	0.08
KBC	0.11	0.18	0.09	0.14	0.16	0.13
la Caixa	0.08		0.08	0.09		0.09
LB Baden-Württemberg	0.09	0.13	0.06	0.10	0.12	0.08
LB Berlin	0.11	0.14	0.10	0.13	0.13	0.13
LB Hessen-Thüringen	0.11	0.19	0.07	0.13	0.18	0.08
Natexis	0.18	0.17	0.22	0.18	0.18	0.19
National Bank of Greece	0.12	0.19	0.09	0.14	0.17	0.12
Natixis	0.11	0.15	0.09	0.14	0.17	0.13
Nordea	0.11	0.17	0.08	0.12	0.15	0.08
Nord LB	0.10	0.18	0.07	0.13	0.16	0.10
Pohjola	0.08		0.08	0.08		0.08
Rabobank	0.11	0.21	0.07	0.16	0.19	0.12
RBI	0.10	0.14	0.09	0.12	0.13	0.11
RBS	0.08		0.08	0.09		0.09
Sanpaolo IMI	0.14	0.14		0.13	0.13	
Societe Generale	0.11	0.18	0.08	0.16	0.21	0.12
Svenska	0.12	0.17	0.10	0.13	0.16	0.11
UBI Banca	0.06		0.06	0.06		0.06
UBS	0.10	0.17	0.06	0.14	0.17	0.10
Unicredit	0.12	0.17	0.09	0.13	0.16	0.11
West LB	0.12	0.17	0.10	0.13	0.16	0.11

Table 10. Potential manipulation effect for Euribor and all Libor rates

This table shows the manipulation potential measured in basis points for three colluding banks for all fifteen tenors of Libor in ten currencies as well as Euribor. We use the following approach to quantify the manipulation effects: We start out with the observed individual contributions made by the panel banks to the final rate. Then, we change the three lowest observed contributions, making them equal to the highest observed contribution. The difference between the original benchmark rate, given the applied rate-setting procedure and the resulting benchmark rate after changing these three contributions is our measure of the potential effect of manipulation. We report the mean of the potential for all 10 currencies and 15 maturities. Our data set contains the reference rate and the underlying contributions, obtained from Bloomberg and the European Banking Federation for the time period from January 2005 to December 2012.

Libor	**ON**	**1W**	**2W**	**1M**	**2M**	**3M**	**4M**	**5M**	**6M**	**7M**	**8M**	**9M**	**10M**	**11M**	**12M**
AUD	5.85	4.41	4.09	3.79	3.52	3.50	3.71	4.13	4.11	4.54	4.85	4.82	4.93	4.86	4.82
CAD	2.27	1.81	1.70	1.54	1.50	1.53	1.68	1.77	1.91	2.04	2.16	2.32	2.37	2.30	2.28
CHF	1.91	1.56	1.59	1.50	1.50	1.78	1.97	2.17	2.42	2.43	2.35	2.32	2.19	2.08	1.93
DKK	8.01	3.79	3.70	3.18	2.93	3.24	3.26	3.07	3.20	3.23	3.30	3.39	3.51	3.66	4.02
EUR	1.82	1.29	1.32	1.31	1.42	1.53	1.57	1.60	1.62	1.66	1.69	1.71	1.77	1.84	1.92
GBP	1.20	1.19	1.20	1.11	1.16	1.31	1.30	1.31	1.41	1.43	1.88	1.54	1.61	1.67	1.71
JPY	1.46	1.31	1.19	0.99	1.02	1.05	1.14	1.20	1.29	1.34	1.39	1.42	1.46	1.54	1.54
NZD	7.29	5.58	4.98	4.72	4.48	4.41	4.52	4.30	4.36	4.64	4.92	5.18	5.39	5.21	5.23
SEK	4.95	4.18	4.20	4.16	4.43	4.77	4.78	4.79	4.69	4.58	4.72	4.61	4.53	4.60	4.78
USD	1.90	1.88	1.84	1.61	1.53	1.61	1.52	1.49	1.52	1.56	1.63	1.74	1.89	2.03	2.19
Euribor	**1W**	**2W**	**3W**	**1M**	**2M**	**3M**	**4M**	**5M**	**6M**	**7M**	**8M**	**9M**	**10M**	**11M**	**1Y**
	0.55	0.53	0.54	0.50	0.53	0.53	0.53	0.53	0.55	0.56	0.56	0.57	0.58	0.59	0.60

Table 11. Potential manipulation effect for static rate-setting procedures

This table shows the means and standard deviations of the potential manipulation effects measured in basis points for various rate-setting procedures, for the three month AUD Libor, USD Libor and Euribor, evaluated for each day. We compare the methodology currently applied (i.e., a trimmed mean), with an untrimmed mean, the median and a random draw. We use the following approach to quantify the manipulation effects for a given methodology: We start out with the observed individual contributions made by the panel banks. Then, we change the lowest observed contribution, making it equal to the highest observed contribution, for the case of a manipulation by one bank. The difference between the original benchmark rate for the rate-setting procedure in question and the resulting benchmark rate after changing this one contribution is our measure of the potential effect of manipulation. We use the same approach when considering the manipulation potential for two or three banks, i.e., we set the lowest two (or three) contributions equal to the highest observed contribution. Our data set contains the reference rates and the underlying contributions, obtained from Bloomberg and the European Banking Federation for the time period from January 2005 to December 2012.

		AUD		**USD**		**Euribor**	
Method	**Banks**	Mean	Std	Mean	Std	Mean	Std
Untrimmed Mean	1	1.49	1.42	0.78	0.88	0.38	0.31
	2	2.51	2.33	1.43	1.61	0.71	0.57
	3	3.32	3.04	2.01	2.27	1.01	0.81
Trimmed Mean	1	1.16	1.25	0.48	0.58	0.17	0.16
	2	2.44	2.36	1.01	1.15	0.35	0.32
	3	3.50	3.33	1.61	1.83	0.53	0.47
Median	1	0.96	1.33	0.31	0.47	0.08	0.24
	2	2.10	2.49	0.74	1.00	0.18	0.38
	3	3.93	3.80	1.28	1.62	0.27	0.46
Random Draw	1	1.09	3.26	0.42	2.62	0.17	0.44
	2	2.28	3.85	0.99	2.85	0.38	0.72
	3	3.49	4.42	1.58	3.53	0.55	0.94

Table 12. Potential manipulation effect for dynamic rate-setting procedures

This table shows the means and standard deviations of the potential manipulation effects measured in basis points, for the dynamic rate-setting approaches, for three month AUD Libor, USD Libor and Euribor. In these dynamic approaches, we exclude submissions based on the time-series, and subsequently submissions based on the remaining cross-section, using the trimmed mean and median. As time-series outliers we exclude the submissions with the highest absolute change from the previous day. We exclude the same number of banks as are excluded in the original trimming procedure, and apply equal proportions of cross-sectional and time-series exclusions. For each day, we report the impact one, two or three colluding banks could have on the final fixing. We use the following approach to quantify these effects: We start out with the observed individual contributions made by the panel banks. Then, we change the lowest observed contribution, making it equal to the highest observed contribution. The difference between the final rates with and without manipulation is our measure of the potential effect of manipulation. Our data set contains the reference rate and the underlying contributions, obtained from Bloomberg and the European Banking Federation for the time period from January 2005 to December 2012.

		AUD		**USD**		**Euribor**	
Method	**Banks**	Mean	Std	Mean	Std	Mean	Std
	1	0.79	1.21	0.24	0.41	0.11	0.14
Trimmed Mean	2	1.52	2.01	0.48	0.73	0.21	0.25
	3	2.76	2.84	0.73	1.03	0.31	0.34
	1	0.55	1.29	0.17	0.46	0.04	0.16
Median	2	1.23	2.10	0.34	0.68	0.09	0.27
	3	2.51	3.24	0.53	0.92	0.13	0.33

Table 13. Potential manipulation effects for multi-day window procedures

This table shows the means and standard deviations of the potential manipulation effects measured in basis points, for rate-setting approaches based on multi-day windows for three month USD Libor. We combine four outlier detection methods, i.e., trimmed mean and median based on the presented cross-sectional (static) and time-series (dynamic) procedures, and combine these approaches with a moving average calculation based on multi-day windows of up to five days. For each day, we report the impact one bank could have on the final fixing, assuming that this bank manipulates once in the multi-day window and is able to optimally time this manipulation, i.e., we change the lowest contribution to the highest on the day where this change results in the highest impact. The difference between the final rates with and without manipulation is our measure of the potential effect of manipulation. In addition, we provide the means and standard deviations of the difference between the different multi-day rates and the original Libor rate. Our data set contains the reference rate and the underlying contributions, obtained from Bloomberg and the European Banking Federation for the time period from January 2005 to December 2012.

Method	**Window**	**Impact**		**Libor change**	
	(days)	Mean	Std Dev	Mean	Std Dev
Static trimmed mean	1	0.48	0.58	0.00	0.00
Static trimmed mean	2	0.26	0.30	0.06	1.48
Static trimmed mean	3	0.18	0.21	0.11	2.65
Static trimmed mean	4	0.14	0.16	0.17	3.70
Static trimmed mean	5	0.11	0.13	0.23	4.67
Static median	1	0.31	0.47	-0.02	0.39
Static median	2	0.19	0.27	0.04	1.58
Static median	3	0.15	0.20	0.10	2.74
Static median	4	0.12	0.16	0.16	3.78
Static median	5	0.10	0.13	0.21	4.75
Dynamic trimmed mean	1	0.24	0.41	0.10	0.59
Dynamic trimmed mean	2	0.17	0.25	0.15	1.68
Dynamic trimmed mean	3	0.13	0.19	0.21	2.81
Dynamic trimmed mean	4	0.10	0.15	0.27	3.84
Dynamic trimmed mean	5	0.09	0.13	0.33	4.80
Dynamic median	1	0.17	0.46	-0.02	0.64
Dynamic median	2	0.14	0.30	0.04	1.73
Dynamic median	3	0.12	0.23	0.10	2.87
Dynamic median	4	0.10	0.19	0.16	3.91
Dynamic median	5	0.09	0.16	0.21	4.87

Table 14. Summary of advantages and disadvantages of various rate-setting procedures

This table shows a summary of the findings for the analyzed rate-setting approaches. We provide a short description of the various methodologies and list their most important advantages and disadvantages. In particular, we compare the potential for manipulation and the effect on the benchmark rate across these different rate-setting procedures.

Method	**Description**	**Advantages**	**Disadvantages**
Static Untrimmed Mean	The benchmark rate is calculated as the average of all submissions on a particular day.	• Very simple method.	• Influenced by any outlier or manipulation. • Highest manipulation potential overall.
Static Trimmed Mean	Currently used methodology; average of trimmed submissions on a particular day.	• Influence of outliers is reduced compared to the untrimmed mean.	• Higher potential for manipulation than other methodologies (except compared to the untrimmed mean).
Static Median	Uses the median of all submissions on a particular day.	• Influence of outliers is significantly reduced compared to all other static approaches. • Lowest manipulation potential of all other static approaches. • Only minor effects on the benchmark rate itself, compared to the original rate.	• Some banks (e.g. the median bank) can achieve the maximum manipulation potential with little effort.
Static Random Draw	The benchmark rate is calculated by randomly selecting one of the submissions on a particular day.	• Manipulation outcome becomes more volatile. This might reduce incentives to manipulate.	• On average, manipulation potential is unchanged compared to the trimmed mean. • Benchmark rate becomes more volatile.
Dynamic Approaches	Use previous submissions for outlier detection in addition to the cross-section.	• Substantial reduction of manipulation potential compared to static approaches.	• Small effects on benchmark rate itself, compared to the original rate.
Time Window Approaches	The benchmark rate is calculated as an average of the submissions over multiple days.	• Manipulations taking place on a single day are averaged out over the sample window. • Overall lowest manipulation potential.	• Significant effects on benchmark rate itself, compared to original rate. • Resulting benchmark rate is a moving average and does not respond immediately to economic conditions.

Table 15. Potential manipulation effect based on simulations

This table shows the parameters (mean and standard deviation measured in basis points, and kurtosis) used for the simulation study, and compares the observed manipulation potential measured in basis points for the three month USD Libor to the simulated manipulation potential. We simulate $20,000$ runs for a panel that is calibrated to this particular Libor rate. In each run, we simulate 16 submissions using a t-distribution. We match the mean and standard deviation to the observed Libor rate submissions during the sample period. We calibrate the degrees of freedom to the average kurtosis based on standardized submissions. We calculate the manipulation potential of three banks colluding based on the original data, simulated data and pre-manipulated simulated data. In the pre-manipulated case, we assume that three banks have already submitted upwardly manipulated submissions on a fraction of 0.2 of all days. We then consider these three sets of submissions as given, and estimate the manipulation effects by changing the three lowest observed contributions, making them equal to the highest contribution. The difference between the final rates with and without this manipulation is our measure of the potential effect of manipulation. Our data set contains the reference rate and the underlying contributions, obtained from Bloomberg for the time period from January 2005 to December 2012.

Parameters	**Mean**	**Std Dev**	**Kurtosis**
3M USD Libor	235	3.42	1.56
Simulation (Student's t with 8 df)	235	3.42	1.50
Manipulation Potential	**Untrimmed Mean**	**Trimmed Mean**	**Median**
3M USD Libor	2.01	1.61	1.28
Simulation	2.02	1.69	1.51
Simulation (pre-manipulated data)	1.92	1.80	1.64