The Impact of HFT on the Speed of Adjustment to New Information: Evidence from Interest Rate Derivatives

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Abstract

This study investigates the impact of HFT on the intraday speed of adjustment and price discovery following scheduled macroeconomic announcements for interest rate derivatives. Our results demonstrate that the speed of adjustment to new information has been improved for both interest rate derivatives, exchange-traded futures and over-the-counter (OTC) traded swaps, in the presence of HFT. In addition, we examine the lead-lag effects between swaps and futures during macro information releases in the pre- and post-colocation periods. We find that HFT strengthens the lead effects of futures on scheduled announcement days.

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1. INTRODUCTION

Over the last decade, financial markets have been transformed due to the introduction and growth of high frequency trading (HFT). Co-location is an important technology upgrade for high frequency traders due to the fact that it significantly reduces latency and allows traders to respond more rapidly to information releases. The characteristics of trading have changed following the introduction of co-location facilities through various channels. First, the improvement in latency enables high frequency traders to adjust their prices more rapidly when new information arrives and therefore improves price discovery efficiency (Chaboud et al., 2014, Chordia, Green & Kottimukkalur, 2016; Brogaard, Hendershott & Riordan, 2014; Frino et al., 2016). Second, as market makers are able to trade faster following the introduction of co-location, market liquidity has been improved (Brogaard, 2010; Brogaard, Hendershott & Riordan, 2014; Riordan & Storkenmaier, 2012; Frino, Mollica & Webb, 2014; Brogaard, Hagströmer, Nordén, & Riordan, 2015; Hendershott, Jones & Menkveld, 2011).

Scheduled announcements represent a very different informational environment relative to normal trading days. A small but growing body of literature has examined the role of HFT in forming prices and providing liquidity when information arrives. Chaboud et al. (2014) and Scholtus et al. (2014) both investigate the impact of HFT on price dynamics on macro announcement days, and find mixed results on the effects of HFT: positively, HFT improves price discovery and increases depth and trading volume immediately after news releases; negatively, HFT might deteriorate volatility around information arrivals. We extend previous studies and provide evidence from Australian derivatives markets. While Frino el al. (2014) has demonstrated that HFT improves liquidity in Australian futures market, our focus is to test the impact of HFT on the speed of adjustment and price discovery following scheduled macro releases.

Subsequent studies examine the market behavior for earnings announcement days across various stock markets. Frino et al. (2017) examine the responses of HFT to firm specific news and find that high frequency traders react faster and more accurately to earnings announcements than non-HFT traders. Frino, Mollica, Monaco and Palumbo (2017) investigate minute-intervals surrounding earnings announcements in Italian stock market and reveal an improvement in market depth following macro releases in the presence of HFT. Our paper extends previous intraday studies in equity markets to interest rate derivatives markets. Interest rate futures have a number of unique features that may lead to differences in the speed of adjustment to new information, relative to equities. First, futures are more sensitive to new information and tend to lead the underlying spot market (Frino & West, 2003). Second, the intraday patterns in interest rate futures are more responsive to macro announcements (Ederington & Lee, 1993 & 1995) compared to equities (Andersen, et al., 2000).

Our paper is different from previous studies that examine firm specific announcements (Frino et al., 2017 and Frino, Mollica, Monaco and Palumbo, 2017). We document the intraday liquidity adjustment following macro announcements. Macro releases are identified as an important type of information that affect prices before anyone can trade on it (French and Roll, 1986). Fleming and Remolona (1999) conjecture that macro announcements do not normally confront market makers with the risk of trading with more informed investors. Consequently, the liquidity provision around macro releases, originated from market makers, is most likely to be driven by inventory control, rather than information asymmetry.

A previous study, conducted by Frino and Garcia (2018), investigates the lead-lag relationship between interest rate futures and swaps. Their study shows that futures market leads swaps market on macro announcement days. In this paper, we extend their work by providing evidence on the role of HFT in price discovery for two related derivatives. Our results show that the speed of adjustment in the aftermath of announcements has been improved for futures market, as well as for the related swaps market, following the introduction of co-location facilities. We conjecture that a reduction in latency in futures has led to an enhancement in price efficiency for OTC-traded swaps through cross-market arbitrage. In addition, we find that HFT strengthens the lead effects of futures on days with new information releases.

The outline of this paper is as follows. Section 2 provides an overview of data and methodology. Section 3 presents the descriptive statistics on SWAPs and BABs futures, and reports regression results. Section 5 reviews concluding remarks.

2. DATA AND METHOD

The data for this study are sourced from the Thomson Reuters Tick History Data Base (TRTH) maintained by the Securities Industries Research Centre of Asia-Pacific (SIRCA). From this dataset we collect intraday bid and ask price, bid and ask size, and traded price and volume for the Australian 90-day bank accepted bill (90-day BABs) futures contracts traded on the Australian Security Exchange (ASX) from 2 March 2010 to 19 February 2014.[1] Over-the-counter (OTC) quote data for the Australian 1-year interest rate swap contract is also collected from TRTH on an intraday basis for the

[1] Although the 90-days BABs futures is traded on a quarterly expiration cycle (March, June, September and December), we implement this study using the nearby futures contract and roll to the deferred contract at expiry date. In order to remove outliers in the futures dataset, we include days on which there are less than 10 contracts transacted, and observations with bid-ask spreads smaller than the minimum tick.

period 2 March 2010 to 19 February 2014. This database includes indicative quotes provided by approved dealers and contributors.[2] For both swaps and futures contracts, we calculate the mid-quote as the average of the best bid and ask quotes which reduces the effect of bid-ask bounce (Hauptfleisch, Putnins and Lucey, 2016). Data for interest rate swap and futures contracts are collected for the daytime trading session from 8:28 am AEST to 4:30 pm AEST.

This study investigates the impact of the increase in high frequency traders (HFT) after co-location was introduced in Australia on price volatility, market liquidity and price discovery. Using the introduction of co-location in Australia on the 20 February 2012, we divide the period 2 March 2010 to 19 February 2014 into two sub-periods. The period from 2 March 2010 to 19 February 2012 is classified as the "Pre Co-location" sample, and the period from 21 February 2012 to 19 February 2014 is classified as the "Post Co-location" sample.

Macroeconomic announcements are collected from the Australian Bureau of Statistics (ABS) and includes the date, announcement type and release time for major macroeconomic announcements in Australia. Following Frino and Hill (2001), we select the types of announcements with a significant impact on market volatility. On this basis, the selected six types of announcements are: Consumer Price Index, Gross Domestic Product, Producer Price Index, Retail Sales, Building Approvals, RBA rate, and Unemployment Rate. In total, there are 159 macroeconomic information releases between 2 March 2010 and 19 February 2014, in which 79 announcements occur in the pre co-location period and 80 in the post co-location period.[3]

2.1. Message Traffic

During the sample period from 2 March 2010 to 19 February 2014, the Australian futures market experienced significant improvements in the speed of trading and dramatic growth in HFT, stimulated by the introduction of co-location facilities on 20 February 2012. As HFTs cannot be explicitly identified in the Australian futures data which remains an anonymous market, this analysis employs message traffic to measure HFT.[4] The HFT proxy is then used to quantify the change in the extent of HFT in the Australian interest rate futures market. In this study, message traffic is defined as the sum of changes in the order book for each one-minute interval. The larger the message traffic is, the more active high frequency traders are.

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[2] Indicative quotes are expressed in yields in the OTC swap market, therefore, we convert the quotes to prices by deducting the yield from 100 (ASX, 2017).
[3] All the announcements are released at 11:30 am AEST, therefore, the announcements are not affected by the pre-market opening and closing phases.
[4] Message traffic includes new order submissions, modifications and cancellations.

2.2. Volatility

The measure of volatility is calculated following McInish and Wood (1992) as the standard deviation of mid-point quotes during each five-minutes interval:

$$Volatility_t = \sqrt{\frac{\sum_{i=1}^{n}(Q_i - \bar{Q})^2 t_i}{\sum_{i=1}^{n} t_i}} \qquad (1)$$

where Q_i is the mid-point quote price i, $\bar{Q}$ is the average quote price during interval *t*, t_i is the amount of time Q_i is alive during interval *t*, and *n* is the total number of quotes in interval *t*.

2.3. Bid-Ask Spreads

The impact of high-frequency trading associated with macroeconomic information releases might not only affect volatility, but also market liquidity. An important measure of market liquidity is the bid-ask spread which is a component of trading costs as mentioned in Frino, Jones, Lepone & Wong, 2014. To measure bid-ask spread, we implement a measure similar to McInish and Wood (1992) defined as:

$$BAS_{d,t} = \frac{\sum_{i=1}^{n}\left(Ask_{d,t}^{i} - Bid_{d,t}^{i}\right)}{n_{d,t}} \qquad (2)$$

where $Ask_{d,t}^{i}$ is the ask price *i* in interval *t* of the day *d*; $Bid_{d,t}^{i}$ is the bid price *i* in interval *t* of the day *d*; and $n_{d,t}$ is the total number of quotes in interval *t* of the day *d*.

2.4. Market Depth

Another important measure of market liquidity is market depth (Lee, Mucklow & Ready, 1993).[5] This study calculates market depth for each 5-minutes interval using available quote sizes at the first level as follow:

$$Depth = \frac{\sum_{i}^{n}[(Bid\ Size_{d,t}^{i} + Ask\ Size_{d,t}^{i})/2]}{n_{d,t}} \qquad (3)$$

where $Bid\ Size_{d,t}^{i}$ and $Ask\ Size_{d,t}^{i}$ are the bid and ask sizes at price *i* in interval *t* of the day *d*, and $n_{d,t}$ is the total number of quotes in interval *t* of the day *d*.

[5] Market depth is estimated only for the futures market since ask and bid sizes are not available for the OTC swap market.

2.5. Intraday Analysis and Estimated Parameters

In order to measure the effect of HFT activity on market quality around macroeconomic information announcements, we evaluate intraday volatility and liquidity (bid-ask spread and depth) around the release time of the reports before and after the introduction of co-location. Following Gajewski (1999) and Frino et al. (2017), we measure volatility and liquidity as the difference between the actual value and a benchmark value. The benchmark value is estimated using observations from 50 to 20 minutes prior to each information release. This benchmark is implemented to standardize the volatility and liquidity measures for each macroeconomic announcement. Specifically, excess volatility and liquidity are estimated as:

$$Excess_{d,t} = Actual_{d,t} - Benchmark_d \quad (4)$$

where $Actual_{d,t}$ is the actual value for volatility, bid-ask spread or depth in minute interval t for announcement d, and $Benchmark_d$ is the mean volatility, bid-ask spread or depth calculated from interval -50 to -20 on announcement day d.

2.6. Price Matched Samples

It may be possible that the level of unexpected information or the value of information on announcement days during the pre-colocation period is systematically different to announcements days in the post-colocation period. To make sure that the size of the information is similar across the two sub-periods, we match each announcement day in the pre-colocation period to an announcement day in the post-colocation period with the closest return. To ensure a close match, any matched returns that differ by more than 4 bps are eliminated from the final sample. The purpose of this procedure is to control for the magnitude of the price movement associated with the macroeconomic announcement releases. We calculate returns using the last traded price 30 minutes prior to the announcements and the last traded price 30 minutes after the announcement is released.

We also control for the size of the information released across the experimental (announcement days) and control (non-announcement days) samples by matching each announcement day to a non-announcement day with the closest return. Returns on non-announcement days are calculated using the last traded price 30 minutes prior and post to the time when announcements are usually released on announcement days. The final sample for the futures market consists of 63 announcements and matched control days for the pre-colocation period, and 57 announcements and matched control days for the post-colocation period. Similarly, the final sample for the swap market consists of 54 announcements and matched control days for the pre-colocation period and 54 announcements and matched control days for the post-colocation period.

2.7. Modelling Price Discovery

Based on prior research, we implement a lead/lad model as in Frino, Walter and West (2000) that investigates the impact of co-location on the price discovery relationship between the swap and futures markets during macroeconomic information releases. Coefficients of the lead/lag model are calculated by regressing measures of 1-minute swap prices against lagged, contemporaneous and leading futures prices as follows:

$$\Delta S_t = \alpha + \sum_{k=-20}^{20} \beta_{t+k}\, \Delta F_{t+k} + u_t \tag{5}$$

where ΔS_t is the change in the swap price over interval t, ΔF_t is the change in the futures price over interval t, and u_t is the error term.[6] Under the lead/lag equation, the futures market leads the swap market when the k < 0 coefficients (lagged futures prices) are significant while the k > 0 coefficients (lead futures prices) are insignificant. Alternatively, the swap market leads the futures market, when the k < 0 coefficients (lagged futures prices) are insignificant while the k > 0 coefficients (lead futures prices) are significant.

3. RESULTS

3.1. Descriptive Statistics

Descriptive statistics are presented for futures and swap contracts and are based upon data in the four-year period from 2 March 2010 to 19 February 2014, coinciding with a 48-month event window centred on the introduction of co-location facilities in the Australian futures market. Table I reports the average number of quotes, volatility, level 1 quoted depth, quoted bid-ask spread and messages for swap and futures contracts during the pre and post co-location periods. Statistics are presented in Table I for all trading days (Panel A), only announcement days (Panel B), a 1-hour window surrounding announcement releases (Panel C), and non-announcement days (Panel D).

Table I shows that message traffic increases for BABs futures contracts from an average of 2338 intraday 1-minute messages to 3785 following the introduction of co-location. This is consistent with

[6] We ignore the 20 minutes around trading breaks to prevent comparing prices across market breaks (Frino, Walter and West, 2000).

previous literature that demonstrates an increase in HFT activity after the introduction of co-location in Australia (Frino, Mollica and Webb, 2014). Overall, we observe a significant reduction in the average daily volatility following co-location for both swap and futures contracts. Similarly, there is an improvement in the liquidity measures with a significant reduction in bid-ask spread for both swaps and futures, and an increase in market depth for the futures market. These results demonstrate that the introduction of co-location not only improves market quality in the futures market, but also has a positive impact on liquidity and volatility in the swap market.[7]

<INSERT TABLE I>

3.2. Magnitude of Information Content Across Sub-Periods

It might be possible that the value of information released in macroeconomic announcements is systematically different before and after co-location which could bias results. To test for this, we compare the absolute mean returns for each sub-period around the time that macroeconomic information is released. Specifically, we calculate the return using the mid-quoted price 30 minutes before the macroeconomic announcement and 30 minutes after the announcement is released.[8] In Table II, we compare the magnitude of price changes on announcement days (Experimental sample) and non-announcement days (Control sample) for interest rate futures (Panel A) and swaps (Panel B) during the pre and post colocation periods. Although there are some differences between the absolute average returns across the two periods, t-statistics testing the mean difference of returns are not statistically significant for both swaps and futures. This implies that the magnitude of the macroeconomic information releases across the two sub-periods cannot explain any observed results.

<INSERT TABLE II>

3.3. The Impact of High Frequency Trading on Price Volatility

Table III reports the average mid-quoted price volatility for each 5-minute interval around the release of macroeconomic information on both announcement days (Experimental sample) and non-announcement days (Control sample) for the periods before and after co-location. Results show that, before co-location, the difference in volatility across announcement and non-announcement days for

[7] Given the implied relationship that exists between the interest rate swap and futures markets, the introduction of co-location in the futures market is expected to also have an impact on the OTC swap market.

[8] Since reports are released at 11:30 am AEST, returns are calculated using the mid-quoted price at 11:00 am AEST and 12:00 pm AEST for both swaps and futures. Table II does not include RBA announcement since this type of announcements occur on days when other announcements are also released at 2:30 pm. To avoid overlapping announcements with different release time, Table III, Table IV and Table V do not include RBA announcements in the analysis.

the futures market is statistically significant for up to 5 minutes leading to the release of information and 15 minutes following information releases. After co-location, the difference in volatility across sub-periods is reduced to 5 minutes following information releases. Results demonstrate that the introduction of co-location reduces the time required for volatility to return to equilibrium in the futures market. Similarly, results for the swap market show that, before co-location, the difference in volatility across announcement and non-announcement days is statistically significant for up to 10 minutes leading to the release of information and 50 minutes following information releases. After co-location, the difference in price volatility across sub-periods is reduced to only 30 minutes following information releases. Results demonstrate that the introduction of co-location not only reduces the time required for volatility to return to equilibrium in the futures market, but also reduces the time required for adjustment in the swap market.

<INSERT TABLE III>

3.4. The Impact of High Frequency Trading on Bid-Ask Spreads

Table IV reports the average bid-ask spreads for each 5-minute interval around the release of macroeconomic information on both announcement days (Experimental sample) and non-announcement days (Control sample) for the periods before and after co-location. Results show that, before co-location, the difference in bid-ask spreads across announcement and non-announcement days for the futures market is statistically significant for up to 5 minutes leading to the release of information and 50 minutes following information releases. After co-location, the difference in bid-ask spreads across sub-periods is reduced to 10 minutes following information releases. Results demonstrate that the introduction of co-location reduces the time required for bid-ask spreads to return to equilibrium in the futures market.

<INSERT TABLE IV>

3.5. The Impact of High Frequency Trading on Market Depth

Table V reports the average depth for each 5-minute interval around the release of macroeconomic information on both announcement days (Experimental sample) and non-announcement days (Control sample) for the periods before and after co-location. Results show that, before co-location, the difference in depth across announcement and non-announcement days for the futures market is statistically significant for up to 5 minutes leading to the release of information and 10 minutes following information releases. After co-location, the difference in depth across sub-periods is reduced to 5 minutes leading to the release of information and 5 minutes following information releases. Results demonstrate that the introduction of co-location reduces the time required for market depth to return to equilibrium in the futures market.

<INSERT TABLE V>

3.6. The Impact of High Frequency Trading on Price Discovery

Table V shows that when the lead-lag model is estimated on announcement days during the two-years period before co-location, five lagged futures prices (k=-1 to k=-5) are significantly positive, which implies that the futures market leads the swap market by up to five minutes. Additionally, coefficients on two lead futures prices (k=+1 to k=+2) are significantly positive at the 0.01 level, suggesting a two minutes feedback from the swap market to the futures market. These results demonstrate that the futures market leads price discovery on announcement days during the period before co-location. When the lead-lag model is estimated on announcement days during the two-years period after co-location, one additional lag futures prices (k=-6) become significantly positive, implying that the lead of the futures market increases after co-location. Additionally, coefficients on one lead futures prices (k=+3) becomes significantly positive at the 0.01 level after co-location is introduced, suggesting that the lead of the futures market increases after co-location. These findings indicate that co-location increases the speed at which information is incorporated not only into the futures markets but also into the swap market, however, the futures market leads price discovery on macroeconomic information releases before and after co-location is introduce.

<INSERT TABLE VI>

4. CONCLUSION

The introduction of co-location in Australia creates a natural experiment in which it is possible to test the impact of HFT on the speed of adjustment to new information. We find that following the introduction of co-location, there is an improvement in the speed at which volatility, bid-ask spread and depth return to equilibrium for both interest futures and swaps. In addition, we examine price discovery by looking at the lead-lag effects between the swap and futures markets during information releases in pre- and post-colocation periods. We find that HFT increases the speed at which information is incorporated into the futures market, and therefore, strengthens the lead effects of futures on scheduled news release days.

APPENDIX

A.I: INSTITUTIONAL DETAILS

The Australian 90-day bank accepted bill futures contract, introduced in 1979, has become one of the most liquid contracts in the world, trading a daily average of 114,805 contracts in 2017, six times higher than the daily average turnover of the SPI futures contract (AFMA, 2017). The 90-day futures contract trades at the ASX Trade24 on a quarterly expiration cycle (March, June, September and December) from 8:28 am AEST to 4:30 pm AEST, and 5:08 pm AEST to 7:00 am AEST during the winter period from the second Sunday in March until the first Sunday in November, as well as from 8:28 am AEST to 4:30 pm AEST, and 5:08 pm AEST to 7:30 am AEST during the summer period from the first Sunday in November until the second Sunday in March.

Australian interest rate swaps are mostly traded in the over-the-counter market. Swap trading comprises regular voice dealer trading and exchange-like trading platforms with central limit order books. In Australia, swap trading is dominated by voice dealers, and only a small proportion of trades is executed on exchange-like trading platforms, including the Australian Market Licence (AML) regime, swap execution facilities (SEF) and multilateral trading facilities (MTF).

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TABLE I

Descriptive Statistics of 1-Year SWAPs and BABs Futures

	1-year Interest Rate Swaps			90-day Bank Accepted Bills Futures			
	# Quotes	**Volatility**	**Quoted Spread (bps)**	**Message**	**Volatility**	**Quoted Spread (bps)**	**Level 1 Depth**
Panel A. All Days							
Pre	289	0.016	4.48	2338	0.012	1.02	1379
Post	287	0.009	2.91	3785	0.009	1.01	2200
All	288	0.012	3.64	3067	0.010	1.02	1793
Panel B. Announcement Days							
Pre	339	0.023	4.31	2617	0.022	1.02	1373
Post	477	0.017	3.08	4192	0.015	1.02	2037
All	410	0.020	3.71	3402	0.019	1.02	1715
Panel C. Announcements (News Release Window)							
Pre	77	0.017	4.41	666	0.013	1.06	1089
Post	120	0.012	3.00	999	0.011	1.04	1734
All	90	0.013	3.66	837	0.012	1.05	1421
Panel D. Non - Announcement Days							
Pre	282	0.013	4.27	2056	0.008	1.02	1398
Post	328	0.009	3.05	3522	0.006	1.01	2403
All	305	0.011	3.74	2752	0.007	1.02	1875

Note. Table I documents summary statistics of liquidity variables for interest rate swaps and futures during the two-years “Pre” co-location period from 2 March 2010 to 19 February 2012, the two-years “Post” co-location period from 21 February 2012 to 19 February 2014, and the four-years period (“All”) around colocation from 2 March 2010 to 19 February 2014. Table I reports volatility as the standard deviation of mid-quoted prices, quoted spread as the difference between the best prevailing quotes, level 1 depth as the average of the ask and bid sizes, and message as the number of records. Summary statistics of liquidity variables are presented for all days in each sample in Panel A, only announcement days in Panel B, 30 minutes before and after announcements in Panel C, and non-announcement days in Panel D.

TABLE II

Comparison of Magnitude of Information Content Before and After Co-location

	Experimental Sample			**Control Sample**		
	Mean (bps)	S.D (bps)	Obs	Mean (bps)	S.D (bps)	Obs
Panel A. Futures						
Pre Co-location	1.29	1.32	63	1.00	0.67	63
Post Co-location	1.02	0.88	57	0.89	0.87	57
Mean Difference	-0.27			-0.11		
T-Value	-1.33			-0.77		
Panel B. Swaps						
Pre Co-location	1.46	1.05	54	1.49	0.74	54
Post Co-location	1.67	0.89	54	1.48	0.73	54
Mean Difference	0.21			-0.01		
T-Value	1.09			-0.02		

Note. Table II reports the sample absolute mean returns in basis points on announcement days (Experimental Sample) and non-announcement days (Control Sample) for the "Pre Co-location" period from 2 March 2010 to 19 February 2012 and the "Post Co-location" period from 21 February 2012 to 19 February 2014. Returns are calculated using quoted prices 30 minutes prior to the announcement and 30 minutes after the announcement is released. Part A presents the difference in absolute mean returns for the 90-day Bank Accepted Bills Futures, while Part B reports the difference in absolute mean returns for the 1-year interest rate swaps.

TABLE III

Intraday Excess Volatility for BABs Futures and 1-Year SWAPs

	Before Co-location					After Co-location			
	Experimental Sample	Control Sample	Difference	T-statistics		Experime ntal Sample	Control Sample	Difference	T-statistics
Panel A. Futures									
-3	-0.0001	0.0003	0.000	-1.271	-3	0.00019	-0.00020	0.000	1.383
-2	0.0005	0.0000	0.000	1.372	-2	0.00014	-0.00024	0.000	1.217
-1	0.0012	0.0001	0.001	3.004***	-1	0.00081	0.00013	0.001	1.934
0	0.0027	0.0007	0.002	3.704***	0	0.00271	0.00075	0.002	4.076***
1	0.0014	0.0001	0.001	3.384***	1	0.00096	0.00035	0.001	1.577
2	0.0012	0.0001	0.001	2.336**	2	0.00057	0.00043	0.000	0.356
3	0.0005	0.0003	0.000	0.576	3	0.00034	0.00037	0.000	-0.076
4	0.0003	0.0000	0.000	0.966	4	0.00030	-0.00024	0.001	1.695
5	0.0004	-0.0002	0.001	1.689	5	-0.00009	-0.00018	0.000	0.285
6	0.0005	-0.0001	0.001	1.826	6	-0.00001	0.00002	0.000	-0.078
7	0.0003	-0.0002	0.001	1.878	7	-0.00003	0.00001	0.000	-0.113
8	0.0005	-0.0003	0.001	1.930	8	-0.00021	-0.00033	0.000	0.428
9	0.0004	-0.0002	0.001	1.746	9	-0.00011	-0.00019	0.000	0.286
Panel B. Swaps									
-3	-0.0004	0.0010	-0.001	-1.542	-3	0.0003	-0.0009	0.001	2.276
-2	0.0006	-0.0008	0.001	2.123**	-2	0.0002	-0.0004	0.001	1.175
-1	0.0016	-0.0001	0.002	2.222**	-1	0.0008	0.0000	0.001	1.442
0	0.0031	-0.0001	0.003	4.166***	0	0.0047	0.0006	0.004	4.654***
1	0.0023	0.0003	0.002	2.2**	1	0.0017	0.0002	0.002	2.721***
2	0.0013	-0.0003	0.002	2.278**	2	0.0011	-0.0007	0.002	3.398***
3	0.0020	-0.0009	0.003	3.06***	3	0.0014	-0.0006	0.002	3.422***
4	0.0014	-0.0015	0.003	2.947***	4	0.0010	0.0003	0.001	1.017
5	0.0012	-0.0005	0.002	2.119**	5	0.0008	-0.0005	0.001	2.325**
6	0.0015	-0.0007	0.002	2.226**	6	0.0005	-0.0001	0.001	0.776
7	0.0003	-0.0014	0.002	1.763	7	0.0003	-0.0007	0.001	1.856
8	0.0014	-0.0012	0.003	3.021***	8	0.0001	-0.0008	0.001	1.376
9	0.0001	-0.0023	0.002	3.357***	9	0.0003	-0.0007	0.001	1.731

Note. Table III reports the intraday average excess volatility for the "Pre Co-location" period from 2 March 2010 to 19 February 2012 and the "Post Co-location" period from 21 February 2012 to 19 February 2014. Volatility is measured as the standard deviation of the mid-quoted prices for each 5-minute interval. Differences between announcement days (Experimental Sample) and non- announcement days (Control Sample), along with the *t*-statistics, are provided. ** $p < 0.05$, *** $p < 0.01$.

TABLE IV

Intraday Excess Bid-Ask Spreads for BABs Futures and 1-Year SWAPs

	Before Co-location					After Co-location			
	Experimental Sample	Control Sample	Difference	T-statistics		Experimental Sample	Control Sample	Difference	T-statistics
Panel A. Futures									
-3	0.008	0.005	0.004	0.158	-3	0.033	-0.003	0.036	1.448
-2	0.035	-0.007	0.042	1.630	-2	0.002	-0.012	0.014	0.923
-1	0.115	-0.016	0.131	2.839***	-1	0.096	0.004	0.092	1.775
0	0.113	0.007	0.106	2.237**	0	0.104	0.005	0.099	1.436
1	0.023	-0.013	0.036	2.031**	1	0.033	-0.007	0.040	2.331**
2	0.086	-0.016	0.102	1.369	2	0.010	0.007	0.003	0.203
3	0.023	-0.024	0.047	2.259**	3	0.007	0.007	0.000	-0.004
4	0.051	-0.021	0.072	2.199**	4	0.031	-0.003	0.034	1.028
5	0.012	-0.030	0.041	2.588**	5	0.010	-0.013	0.023	1.960
6	0.025	-0.019	0.044	2.192**	6	-0.014	0.003	-0.017	-0.971
7	0.039	-0.021	0.060	1.979	7	0.000	0.004	-0.004	-0.178
8	0.033	-0.034	0.067	2.667***	8	0.012	-0.008	0.020	0.900
9	0.019	-0.023	0.042	2.136**	9	0.009	-0.010	0.019	0.833
Panel B. Swaps									
-3	-0.415	-0.009	-0.406	-1.251	-3	0.149	-0.123	0.272	1.656
-2	-0.051	0.128	-0.179	-0.471	-2	0.160	-0.076	0.236	1.448
-1	-0.153	0.424	-0.577	-1.570	-1	0.072	-0.004	0.076	0.516
0	-0.106	0.020	-0.127	-0.369	0	-0.219	-0.067	-0.152	-1.213
1	0.159	0.126	0.033	0.098	1	-0.117	-0.053	-0.065	-0.493
2	0.325	-0.041	0.365	1.085	2	-0.047	0.076	-0.124	-0.822
3	0.209	-0.332	0.541	1.491	3	0.093	0.035	0.059	0.386
4	-0.008	0.089	-0.097	-0.259	4	0.066	0.075	-0.009	-0.051
5	-0.022	0.090	-0.112	-0.303	5	0.048	0.070	-0.021	-0.115
6	-0.118	0.211	-0.329	-0.891	6	0.085	-0.038	0.123	0.676
7	-0.319	0.098	-0.417	-1.084	7	0.099	0.099	0.001	0.004
8	0.005	0.104	-0.099	-0.260	8	0.163	0.069	0.094	0.510
9	-0.011	-0.089	0.077	0.196	9	0.140	0.129	0.011	0.054

Note. Table IV reports the intraday average excess quoted bid-ask spread for the "Pre Co-location" period from 2 March 2010 to 19 February 2012 and the "Post Co-location" period from 21 February 2012 to 19 February 2014. The bid-ask spread is calculated for each 5-minute interval using the difference between the best prevailing quotes for the 90-day Bank Accepted Bills Futures and 1-year interest rate swaps. Differences between announcement days (Experimental Sample) and non- announcement days (Control Sample), along with the *t*-statistics, are provided. ** $p < 0.05$, *** $p < 0.01$.

TABLE V

Intraday Excess Depth for BABs Futures Contracts

	Before Co-location					After Co-location			
	Experimental Sample	Control Sample	Difference	T-statistics		Experimental Sample	Control Sample	Difference	T-statistics
Panel A. Futures									
-3	-50.474	17.519	-67.993	-1.118	-3	-2.486	-48.914	46.428	0.413
-2	-110.158	-51.831	-58.327	-0.799	-2	-222.204	-89.914	-132.290	-1.353
-1	-461.571	-122.736	-338.835	-3.736***	-1	-504.815	-145.077	-359.738	-2.895***
0	-457.324	-127.568	-329.756	-3.495***	0	-631.330	-195.177	-436.153	-3.529***
1	-331.042	-101.794	-229.248	-2.471**	1	-371.295	-198.736	-172.560	-1.335
2	-246.458	-96.677	-149.781	-1.774	2	-406.883	-160.028	-246.856	-1.797
3	-167.458	-111.819	-55.639	-0.619	3	-349.149	-172.821	-176.328	-1.308
4	-152.123	-102.806	-49.317	-0.568	4	-380.346	-142.306	-238.039	-1.756
5	-138.649	-153.832	15.182	0.173	5	-346.372	-167.068	-179.304	-1.319
6	-122.055	-147.424	25.369	0.273	6	-207.944	-181.820	-26.123	-0.188
7	-36.196	-135.149	98.953	0.978	7	-184.132	-169.801	-14.330	-0.098
8	-22.823	-88.227	65.405	0.601	8	-168.591	-135.450	-33.141	-0.223
9	-10.939	-83.793	72.854	0.617	9	-161.301	-214.811	53.511	0.349

Note. Table V reports the intraday average excess depth for the "Pre Co-location" period from 2 March 2010 to 19 February 2012 and the "Post Co-location" period from 21 February 2012 to 19 February 2014. Depth is measured for the 90 Days BABs futures using all available quotes at the best level during each 5-minute interval. The number of contributors for each 5-minute interval is used as a proxy of depth for the 1-year interest rate swap. Differences between announcement days (Experimental Sample) and non- announcement days (Control Sample), along with the *t*-statistics, are provided. ** $p < 0.05$, *** $p < 0.01$.

TABLE VI

Price Discovery in the Interest Rate Market Before and After Co-location

Panel A: Coefficients from lead/lag OLS regression

	Pre Co-location		Post Co-location	
	Coefficient	T-statistic	Coefficient	T-statistic
Intercept	0.0000	0.00	0.0000	0.09
$\boldsymbol{\beta}$ t+10	-0.0051	-0.42	0.0089	1.15
$\boldsymbol{\beta}$ t+9	-0.0063	-0.52	0.0061	0.78
$\boldsymbol{\beta}$ t+8	0.0009	0.08	0.0061	0.79
$\boldsymbol{\beta}$ t+7	-0.0091	-0.76	-0.0013	-0.17
$\boldsymbol{\beta}$ t+6	0.0131	1.09	0.0166	2.14
$\boldsymbol{\beta}$ t+5	0.0153	1.28	0.0140	1.81
$\boldsymbol{\beta}$ t+4	0.0215	1.79	-0.0012	-0.16
$\boldsymbol{\beta}$ t+3	-0.0095	-0.79	0.0303	3.90***
$\boldsymbol{\beta}$ t+2	0.0356	2.97***	0.0200	2.58***
$\boldsymbol{\beta}$ t+1	0.0673	5.56***	0.0522	6.73***
$\boldsymbol{\beta}$ t	0.4144	34.30***	0.3152	40.68***
$\boldsymbol{\beta}$ t-1	0.1877	15.53***	0.2176	28.09***
$\boldsymbol{\beta}$ t-2	0.0769	6.36***	0.0457	5.90***
$\boldsymbol{\beta}$ t-3	0.0588	4.875***	0.0340	4.39***
$\boldsymbol{\beta}$ t-4	0.0078	0.65	0.0158	2.04**
$\boldsymbol{\beta}$ t-5	0.0523	4.38***	0.0135	1.74
$\boldsymbol{\beta}$ t-6	0.0213	1.78	0.0249	3.22***
$\boldsymbol{\beta}$ t-7	0.0000	0.00	0.0121	1.57
$\boldsymbol{\beta}$ t-8	0.0166	1.39	0.0115	1.49
$\boldsymbol{\beta}$ t-9	0.0024	0.20	0.0106	1.37
$\boldsymbol{\beta}$ t-10	-0.0343	-2.88	-0.0075	-0.97
Panel B: Hypothesis tests (F-test)				
H1: $\boldsymbol{\beta}$ t+10 = 0		7.79***		21.98***
H2: $\boldsymbol{\beta}$ t-10 = 0		77.01***		137.92***

Note. Table VI reports the regression coefficients of the lead/lag model for the pre and post colocation periods. Panel A presents the coefficients estimated using an OLS regression with 1-minute intraday observations where the dependent and independent variables are the change in the swap price and nearby futures contract price, respectively. Panel B reports the F-statistics of Wald tests on coefficient restrictions for the two hypotheses. ** $p < 0.05$, *** $p < 0.01$.