Intraday timing of AUD intervention by the Reserve Bank of Australia: Evidence from microstructural analyses

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Abstract

We estimate the approximate intraday timing of interventions by the Reserve Bank of Australia (RBA) in the onshore and offshore USD/AUD markets for the period of 1996 to 2006. We use a more accurate measure of intervention that excludes transactions with the government as well as high frequency tick-by-tick quote data on the USD/AUD exchange rate. The RBA’s interventions are detected in the late Sydney onshore period, early European market, and again in the early New York market hours. Furthermore, evidence suggests that the RBA chooses those hours of higher volume, lower volatility and lower bid/ask spreads to conduct its non-intervention transactions. These results have important implications not only for institutions and corporations with a need to transact in the market, but also for hedge funds and other traders that may profit by trading against the RBA.

Keywords: RBA intervention times; Intraday volatility, Volume, bid-ask spread

JEL Classification: E44; G14; G15

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1. Introduction

Foreign exchange interventions by central banks are conducted to address the deficiencies of a freely floating exchange rate regime, the most notable of which are excessive volatility and persistent deviations from the underlying fundamentals. The literature on interventions has focused mostly on the twin pillars of intervention effectiveness and intervention reaction functions. However, most of the early research used daily data frequency in their investigations due to a lack of time stamped intervention data, except for the case of Swiss National Bank interventions (inter alia Bein, 2004; Bonser-Neal and Tanner, 1996; Baillie and Osterberg, 1997; Chang and Taylor, 1998; Dominguez, 1998; Frenkel et. al., 2005). Trend deviations in exchange rates and foreign exchange market volatilities, among other factors, were often identified as some of the determinants of intervention (inter alia Chaboud and Humpage, 2003; Beine, 2004; Frenkel et al., 2005; Kim and Sheen, 2006; Ito and Yabu, 2007, Neely, 2008). Intervention activities, in turn, were commonly found to move the exchange rate often in the wrong direction (a purchase of a currency leading to its depreciation) and to raise volatility on the days of intervention. This was due to the endogeneity of interventions in the studies of intervention effectiveness that used daily aggregates of intervention transactions combined with the same daily frequency of exchange rate return and volatility data (Bein, 2004; Baillie and Osterberg, 1997; Chang and Taylor, 1998; Dominguez, 1998; Frenkel et. al., 2005).

The initial attempts at addressing this issue of simultaneity were to use lagged regressors—one day lag of intervention in the effectiveness estimations and one day lag of returns and volatility in the intervention reaction function estimations (e.g. Lewis, 1995; Baillie and Osterberg, 1997). The literature then reports some evidence of a structural approach to jointly model intervention effectiveness and intervention reaction functions (Kearn and Rigobon, 2005) as well as a data approach to circumvent simultaneity (Kim, et. al,
Central banks often intervene multiple times within a given business day and the market reaction to the first instance of intervention determines whether further action is warranted. In the case of Swiss National Bank, where transaction-level data is available with trade time stamps, it is possible to precisely determine the exchange rate behavior immediately following each intervention transaction in order to ascertain their efficacy (see Fischer, 2006; Fischer and Zurlinden, 1999, Payne and Vitale, 2003). However, no other central bank makes their intraday intervention transactions available to researchers. As a result, researchers have instead used proxies for intervention timing within the day of intervention. For example, Dominguez (2003, 2006) used the Reuters’ newswire flashes as a proxy for the time of intervention and she reports that G3 central banks in her sample (1989 to 1995) mostly intervene during their business hours (Bank of Japan mostly intervenes 1pm Tokyo time, Bundesbank around 12:30 Frankfurt time, and US Fed around 10:30am EST). However, this approach has the shortcoming of not being able to precisely identify the lag between the time of intervention by a monetary authority and the time that the news is released by Reuters (Fischer, 2006). In addition, Neely (2008) reports that for most central banks the intervention response time to market disorderliness is less than two hours.

The Reserve Bank of Australia (RBA) does not publicly announce its intervention activities as they occur, nor does it reveal the intervention times afterwards. Only the daily aggregates of market transaction amounts are released to public with a six-month delay. Some interventions are low key and unknown to the market, whereas others are more prominent, with the RBA’s presence becoming known after some delay (Becker and Sinclair, 2004). The RBA could potentially intervene anytime during a 24-hour period and, in general, its intervention times and the typical microstructural conditions that might induce interventions

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1 For example, first and second moment return behavior as well order flows and transaction volume can be examined over various holding periods (1- 5- 10- 60-minutes) immediately after intervention transactions to ascertain whether interventions have desired short-term consequences (direction of market movements and volatility responses) and ascertain the durations of market adjustments to interventions.
are not known. These would be valuable pieces of information for all levels of participants in the AUD market. In this paper we take an innovative approach to combine analyses on the investigation of the microstructural characteristics of each of the 24 hourly trading horizons with the identification of the RBA’s intraday intervention timing. We expand upon the high frequency methodologies of Dominguez (2006), Beine, et al. (2007), and Beine, et. al. (2009). This approach will shed light on the market conditions within each of 24 one-hour holding periods in a trading day for the AUD that were conducive to interventions. In addition, we also provide the distinct microstructural characteristics that the RBA favors when transacting on behalf of the Commonwealth Government of Australia and other related counterparties.

The principal findings of our analyses are as follows. First, we observe higher exchange rate volatility, trading volume and wider bid-ask spreads at the start and end of each trading day, which is consistent with the microstructure literature. In addition, we find that both volume and volatility peak during the offshore trading period, indicating that the AUD is exposed to the more intense trading activities during offshore hours.

Second, we detect the RBA’s presence during specific segments of the 24-hour trading day. These are the late Australian onshore business period, the early European offshore markets, and the early New York period. We conjecture that by intervening during these hours the RBA provides additional market information to foreign exchange traders so as to allow them to act on it when they begin/close their trading days. These intraday segments show elevated levels of volatility and we postulate that the RBA’s interventions are designed to reduce short-term volatility in order to dictate the market trend for the ensuing trading period.

Third, we identify a broad negative relationship between the non-intervention market transactions of the RBA on the one hand and the volatility of the exchange rate and the average bid-ask spread magnitude at various times of the day on the other. We conjecture that
this represents a preference of the RBA for carrying out their foreign exchange inventory management transactions when exchange rate volatilities are low so as to minimize both their impact on the market and their transaction costs.

The investigation results have important implications for all types of market participants in the AUD/USD market. We have uncovered those specific intraday periods that are optimal for the execution of interventions by the RBA. Moreover, these optimum periods may vary according to the method with which the RBA chooses to intervene (large vs. small interventions; public vs. secret; singular interventions vs. those persisting over multiple days) and whether the motivation for intervention is driven by a desire to reduce market volatility or in order to correct deviations in the level of the exchange rate.

Furthermore, through the analyses of the market characteristics surrounding interventions, guidance can be offered to other non-government participants in the foreign exchange market as to the most advantageous times for them to transact in the presence of a monetary authority that is actively intervening. As intervention has been shown to be a loss-making activity for central banks (Sweeney, 1997; Szakmary and Mathur, 1997) for the short term, the corollary suggests that trading against a monetary authority is a potentially profitable exercise. Therefore, the knowledge of the timing of interventions may be beneficial for hedge funds and other profit-seeking market participants.

The remainder of this paper will proceed as follows. In section 2 we present descriptive analyses of the different data sources employed within this study before detailing the methodology utilized to address our key research concerns. Section 3 presents an evaluation of the intraday microstructural characteristics of the USD/AUD market and then proceeds with the empirical results of our intervention analyses. We conclude in Section 4.
2. Data and methodology

2.1 RBA intervention data

The traditional measure of the RBA intervention transactions used by previous researchers is its daily net market purchases (NMP) of foreign currency (predominantly U.S dollars) in millions of Australian dollars (Edison, 2006; Kearns and Rigobon, 2005, Kim et. al, 2000, Kim, 2007, etc.). Positive values in this series are representative of a net purchase of foreign currency on that day (i.e. a sale of AUD), with negative values representing a net sale of foreign currency (i.e. a purchase of AUD). A graphical representation of this series can be found in Panel B of Figure 1. Our sample period spans the 2,868 business days from 03 January 1996 until 29 December 2006, during which the RBA transacted in the foreign exchange market on 1,024 days; 971 of which were recorded as net purchases of foreign currency in comparison to only 53 days of net sales.

The Reserve bank of Australia (RBA) does not publicly announce its intervention activities as they occur. Some transactions are visible in the market, whereas some others are not. Becker and Sinclair (2004) identify broadly three ways that the RBA conducts its interventions. First, low key interventions are where agent banks are used so that the market is unaware of its presence. Second, the RBA can actively participate in the broker market segment where its presence is immediately known to active players in the interbank market and their clients. Third, the RBA can directly trade against a market-making bank where information spread is slower. The first approach is used when the RBA does not wish to reveal its presence in the market. This is usually the case when it wishes to replenish or unload foreign currency (USD) reserves for portfolio balancing purposes. Alternatively, low key transactions can be ‘secret interventions’ designed to stimulate short-term heterogeneity in the market with the aim of breaking bandwagon effects.² On the other hand, the second

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²The RBA might, on occasion, be unwilling and unable to turn the tide in exchange rate movements. Instead, it
and the third types of interventions would be known to the market contemporaneously, and this will enhance the potential intervention effect. These transactions can be considered ‘public interventions’.  

The RBA identifies two different periods of intervention behavior within our sample period. First, lasting until the end of 2001 was a period where the RBA conducted interventions in order to support the value of the AUD and to achieve market calming. From 2002 until the end of our sample, the RBA has stated that it conducted no intervention transactions in the foreign exchange market. Instead, the RBA sought to rebuild the foreign exchange reserves that it had expended in defense of the AUD over the 1997 to 2001 period (RBA annual reports 2007, 2008). However, the RBA intervened during August 2007 and October and November 2008 when it acted to provide liquidity in a time of high market uncertainty, rather than to alter the actual level of the exchange rate. These occasions would more correctly be described as quantitative easing by the RBA and hence a monetary policy rather than a traditional sterilized intervention. Accordingly, we conduct subsample analyses based on these two periods, with the first subsample spanning the period from 03 January 1996 to 31 December 2001 and the second from 01 January 2002 to 29 December 2006. Further details on these two subsamples can be found in Table 1.

The RBA intervention literature to date has utilized the RBA’s net market purchase may choose to increase residual volatility in the market via ‘secret (or low key) interventions’ so as to discourage some traders (notably liquidity traders) from trading and encourage market participants (especially informed traders) to think that the trend is broken thus achieving the aim of breaking the bandwagon effect leading to an eventual reduction (or calming) of market volatility.

3The RBA has expressed (Becker and Sinclair, 2004; Rankin, 1998) that its intervention policy is such that it is willing to allow sizable fluctuations in the value of the Australian dollar, both on a day-to-day basis and throughout the national business cycle, and that its interventions are conducted in order to signal to the market that the behavior of the exchange rate is misaligned with the behavior of the underlying economic factors.

4The RBA states that it takes into account the presence of persistent volatility, a widening of the bid-ask spread, and erratic movements in the exchange rate when giving consideration to intervention (Becker and Sinclair, 2004; Rankin, 1998).

5Inclusion of the handful (three occasions) of RBA interventions in 2007 and 2008 into the analysis does not have any impact on the expanded whole sample analysis. Furthermore, this later intervention period (2007+) does not provide sufficient number of intervention observations to allow an independent period analysis. Therefore, we define the sample period for the current analysis as being until Dec 2006.
(NMP) transactions in the foreign exchange market which is a daily aggregate of its intervention activities (Edison, 2006; Kearns and Rigobon, 2005, Kim et. al, 2000, Kim, 2007, etc.). The NMP series is composed not only of intervention transactions, but also of those transactions that the RBA has undertaken in order to manage their liquidity requirements and those transactions undertaken on half of the Commonwealth Government of Australia (and other client counterparties). However, Neely (1998) found that the statistical attributes of the data were not altered significantly by the inclusion of these other forms of non-intervention transactions in the case of interventions by the U.S. Federal Reserve. This finding has been the basis in subsequent intervention studies for the use of series that aggregate all transactions that a monetary authority makes with the market as their proxies for intervention activity. In the case of studies that focus on intervention by the RBA, this approach was further justified by the bank itself (Rankin, 1998), which suggests that the discretion the RBA possesses over when to cover government transactions and rebuild their foreign exchange reserves implies that all transactions within this market series should be considered as interventions.

However, the RBA has recently made available a second series that contains solely their transactions with the Australian government and its other clients, which is similarly measured as their net purchases of foreign currencies (predominantly in USD) in terms of AUD each day (Net Purchase from Government, NPG shown in Panel C, Figure 1).6 Over the length of our sample period, the RBA conducted transactions with its clients on 2,656 days (or 92.6% of the sample), where 1,929 days were net sales of USD to their clients and 727 days were net purchases of USD. The large proportion of sales of USD can be accounted for by the need of the Australian government for foreign currency to spend on defense, foreign aid, and the running of its embassies. The vast bulk of these government transactions are small in size, with transactions on 88.4% of those days having observations in this series

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amounting to less than 50 million AUD (see Table 1 for further details).

A comparison of this government transaction series with the market transaction series permits an understanding of the extent to which the RBA’s transactions with dealers in the market are conducted to cover the orders of its clients. In order to get a more accurate representation of the RBA’s intervention activities, a third series should be formed by removing the RBA’s transactions against the government from the net market purchase series. This is done by adding the net market purchase with dealers and net purchased from the government (i.e. addition of the underlying series for Panel B and C). Moreover, the use of the traditional market transaction series as a proxy for intervention activity has become increasingly questionable in the context of more recent RBA releases that indicate they will use agent banks when rebuilding foreign currency reserves in an attempt to hide their presence from the market, thereby limiting the potential market impact that those non-intervention transactions may have (Reserve Bank of Australia, 2007, 2008).

The new intervention series then need to filter out small values. This is evident from the substantially smaller number of transactions that the RBA conducts in the market (1,024 days) relative to the number of transactions that it conducts with the government (2,656 days). Without filtering out these smaller values, taking the difference of the two series would greatly increase the number of transaction days and consequently misrepresent the days on which the RBA ‘intervened’. This effect can be seen through a comparison of Panel B and Panel D of Figure 1.

However, this approach is also not without imperfections, as the RBA acknowledges that it has attempted to time the market in order to achieve the best exchange rate possible, and thus may not cover a position taken from the government on the same day. This becomes

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7The RBA can choose to rebalance its foreign currency transactions against the commonwealth government by taking opposite transactions in the market against dealers. For example, if the RBA sold USD100 m it can purchase the same amount from the market. The NMP series would then record +USD100 and the net purchase from government series would show –USD 100m. Thus, adding the two series would remove the government related transactions from the NMP series.
apparent when making an ‘eye-ball’ comparison of the two original series, with large
government transactions often not being covered in the market for several days. The method
of netting out the government related transactions and then filtering also requires a judgment
to be made about the minimum transaction size to remain in the sample after filtering occurs.\(^8\)

2.2 *High frequency foreign exchange data*

The exchange rate data used is the Reuters’s FXFX tick-by-tick indicative quotes for the
USD/AUD exchange rate obtained from SIRCA for the entire length of the sample.\(^9\) As the
AUD is actively traded around the clock, the use of such high frequency data enables the
disaggregation of the daily AUD trading patterns and the RBA’s intervention behavior in a
manner not previously attempted in the literature.\(^10\) The start date from this data source is
January 1996. Although an alternative data source exists for pre-1996 periods a decision has
been made to use only the post-1996 sample because the AUD indicative quote volume in the
pre-1996 period is insufficient to warrant such in-depth analyses.

Of the 17,720,095 observations in the full series, 17,712,176 remained after
excluding those observations that did not contain both a bid and ask quotation, and this was
further reduced to 16,555,636 after removing those observations that fell during the
Australian weekends. Each quotation was originally accompanied by a date and timestamp
recorded in Greenwich Mean Time, which was then adjusted to Australian Eastern Standard
Time (AEST) with the addition of 10 or 11 hours depending on whether or not Australia was
in daylight savings at the time of the quotation.

The midrate is the average rate between bid and ask quotes, and bid-ask spread is

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\(^8\)We used 50, 100 and 150 million as the three thresholds for filtering the three types of transaction data. We
report only the investigation results using only the interventions greater than AUD 100 million. However, the
results using other thresholds were qualitatively similar.


\(^10\)To the best of our knowledge, there has been no published studies of RBA interventions that utilize tick-by-
tick AUD data.
calculated as the difference between ask and bid quotes divided by bid rate. We divide our entire sample into equal-length holding periods of one hour each, beginning at 12:00:00 AM AEST on 03 January 1996 and ending at 11:59:59.99 PM AEST on 29 December 2006, for a total of 68,832 holding periods. The initial and final midrates (spreads) that fall within the bounds of each hour-long holding period are recorded respectively as the opening and closing midrates (spreads) for that period, thereby effectively treating them as though they fell exactly on the boundaries of the period. Similarly, we record the maximum and minimum midrates (spreads) within each holding period as the high and low observations. Using these figures we are able to generate our main variables of interest.

We define the volume for each holding period as the number of quotes during that one-hour holding period. There is a substantial increase in the number of quotes per holding period across the length of the sample. This could potentially reflect an overall increase in the trading volume of the AUD. Secondly, it could also be due to the shift of foreign exchange business away from the traditional telephonic broking structure toward a system that is more heavily reliant on electronic dealing platforms such as those provided by Reuters and EBS.

The market activity variables that we focus on for the analyses are volume, volatility and average bid-ask spread for the hourly holding periods. We use the Garman and Klass (1980) measure of volatility that utilizes four price observations in each holding period (open, close, high and low) and that is more accurate than the often-used squared returns estimator that utilizes only opening and closing prices. Furthermore, this measure of volatility is comparable to realized volatility. Assuming a geometric Brownian price process, the Garman Klass (GK) volatility estimate can be calculated on the basis of the opening, high, low and closing observations for any given holding period as follows:

$$\hat{\sigma}^2_{(GK),n} = 0.5\left[ \ln \left( \frac{High_i}{Low_i} \right) \right]^2 - \left[ 2\ln(2) - 1 \right] \left[ \ln \left( \frac{Close_i}{Open_i} \right) \right]^2$$  \hspace{1cm} (1)$$

For each type of market activity variable (holding period volume, midrate GK
volatility, and average spread), we construct time series that span the 2,868 days of the sample on the basis of their time of the day. With twenty four holding periods per day, twenty four time series are created for each variable type (0:00:00 AM to 00:59:59 AM, 01:00:00 AM to 01:59:59 AM, etc). Figure 2 illustrates this process of forming the one hour holding periods and consequent time series. By plotting the averages of each of these 24 time series for each of the variables, we are able to graphically analyze the intraday trading characteristics of the Australian dollar.\footnote{Holding periods shorter than one hour in length were also considered (for example: 288 holding periods of 5 minutes per day, 96 holding periods of 15 minutes, and 48 of 30 minutes). However, as our primary intention is to illuminate the approximate times of the day that the Reserve Bank of Australia intervenes, further disaggregation of this type is deemed unnecessary.}

2.3 Time series modeling

In order to ascertain approximate intervention times, we undertake time series regressions that examine the relationship between the daily aggregates of RBA transactions and the hourly microstructural characteristics described above. This will allow us to statistically identify the association between intervention and the hourly market characteristics while mitigating other influences. Although the autoregressive moving average models detailed below make use of multiple explanatory variables (including intervention) in order to predict their effect on the market characteristic variables, the level of inference that can be drawn from this procedure is limited to statements of correlation. Although no causal inferences will be drawn, these correlational relationships are sufficient for the purpose of identifying the approximate timing of the RBA’s interventions and the microstructural characteristics of the foreign exchange market at those times.

As discussed above, we have three series of RBA transactions that can be used for analysis: first, the daily series that contains the aggregate of all RBA transactions with the market (NMP), which has been the traditional measure of intervention; second, the daily
series that contains solely the RBA’s daily transactions with the Commonwealth Government of Australia (Net Purchase from Government, NPG); and third, the NMP excluding NPG (NMPXG), which we utilize as an enhanced proxy for intervention activity.\textsuperscript{12}

We estimate the following two ARMAX (1,1) models for each of the twenty four time periods (see Figure 2):

\[
\sigma^2_{t} + \epsilon_{t} = a_{n} + b_{n} \cdot |Int_{t}| + c_{n} \cdot Vlm_{t,n} + Controls + f_{n} \cdot \sigma^2_{t-1,n} + \epsilon_{t} + f_{n} \cdot \epsilon_{t-1} \tag{2}
\]

\[
AvgSpread_{t,n} = a_{n} + b_{n} \cdot |Int_{t}| + c_{n} \cdot Vlm_{t,n} + Controls + f_{n} \cdot AvgSpread_{t-1,n} + \epsilon_{t} + f_{n} \cdot \epsilon_{t-1} \tag{3}
\]

The dependent variables are our measures of hourly market characteristics: volatility of the midrate and the average spread. As noted, \(t = 1, 2,868\) and \(n=24\). In order to obtain white noise errors, different orders of AR and MA lags were chosen for each model, however, the estimated coefficient for the intervention variable is qualitatively the same as the more parsimonious ARMAX (1,1) framework. Thus, for consistency of presentation, we show only the parsimonious specification of these models.

In light of the established positive relationship between transaction volume and market volatility, we first control for the volume of quotes in the \(n\)’th holding period on day \(t\), \(Vlm_{t,n}\). We also control for several additional factors through the use of dummy variables. First, as macroeconomic announcements are known to cause jumps in the level of market volatility (Andersen, Vega, Bollerslev, and Diebold, 2003; Faust, Rogers, Wang, & Wright, 2007), we control for these scheduled announcements (both Australian and the U.S. news) on day \(t\) (Equations 4, 5 and 6). The five specific factors that we control for are gross domestic product, balance of payments, consumer price index, unemployment and retail sales. Second, we also control for scheduled monetary policy announcements by both the RBA and the U.S.

\textsuperscript{12}In addition to these three series, we have specified four separate magnitudes for the minimum transaction size that warrants being classified as an intervention: any transaction size, greater than 50 million AUD, greater than 100 million AUD, and greater than 150 million AUD. However we find that the results we report do not vary across these different interventions sizes.
Federal Reserve’s FOMC. We also incorporate four dummy variables in order to account for the possibility of day-of-the-week effects in the exchange rate (Equation 6), a pattern identified in the USD/AUD market by Hogan and Batten (2005). This approach to controlling for intraweek seasonality is one we adopt from Beine, et.al (2007).

\[
Controls = \sum_{j=1}^{4} d_j \cdot \text{AnnounceDum}_j + \sum_{k=1}^{4} e_k \cdot \text{DayDum}_k\\
\sum_{j=1}^{4} d_j \cdot \text{AnnounceDum}_j = d_1 \cdot \text{AUMacroDum}_t + d_2 \cdot \text{USMacroDum}_t + d_3 \cdot \text{RBADum}_t + d_4 \cdot \text{FOMCDum}_t\\
\sum_{k=1}^{4} e_k \cdot \text{DayDum}_k = e_1 \cdot \text{Monday}_t + e_2 \cdot \text{Tuesday}_t + e_3 \cdot \text{Wednesday}_t + e_4 \cdot \text{Thursday}_t
\]

As our study is cross-sectional in nature, with every observation within one time series representing the equivalent time period from each trading day (see Figure 2), there is no need to control for intraday seasonality in the form that was proposed by Anderson and Bollerslev (1998). Our primary focus is on coefficients of the intervention variable \((b_n)\) variable for each of the 24 holding periods within each day in equations (2) and (3) above. The results from these ARMAX estimations will be detailed graphically in the next section.

As we have not attempted to address the simultaneity bias, we would expect findings consistent with the literature (Kim et al., 2000; Edison, 2006) such that intervention and exchange rate volatility would be significantly and positively related in those holding periods where the RBA has been inclined to intervene. As the RBA has stated that they intervene both during Australian (onshore) and European (offshore) business hours (Rankin, 1998; Becker and Sinclair, 2004), it could be reasonably expected that significant intervention variable coefficients would be found during both of these periods. Furthermore, some degree of clustering in these coefficients would be anticipated in light of the belief by many central banks that the effect of intervention on volatility persists to a substantial extent beyond our one-hour holding periods. If intervention were to result in an initial increase in market uncertainty, the average bid-ask spread could be expected to widen as dealers attempt to
insulate themselves from losses caused by sudden exchange rate movements originating from the intervention. Alternatively, wider bid-ask spreads are a plausible motivation for intervention by the RBA. Both lines of reasoning would lead to an *a priori* expectation of a positive correlation between intervention and the magnitude of the bid-ask spread. From the perspective of a foreign exchange trader, knowledge of the RBA’s favored intervention timings may permit them to better protect themselves against adverse price movements instigated by intervention or profit from position taking.

### 3. Microstructure of the USD/AUD market

#### 3.1 Intraday trading volume

The first column of Figure 3 shows graphical representations of the average volume of quotes for the 24 one hour holding periods. The results for the whole sample are shown in Panel A, and the two subsample results are shown in Panels B and C. Similar to what Hogan and Batten (2005) documented with a six week sample of quote data, we report three sharp peaks of market activities within the 24-hour period. The first of these peaks corresponds approximately to the middle of the Australian business day (12PM AEST), the second to the end of Australian business hours (5PM), and the third to midnight. In all three samples, it is readily apparent that the vast majority of trading in the USD/AUD exchange rate occurs in the offshore trading periods. Those holding periods within onshore business hours are characterized by having the lowest average trading volumes of the calendar day. The trading volume within our first subsample was distinctly lower than that of our second subsample. This is evident through a comparison of Panels B and C, whereby the average number of quotes per holding period in the second subsample is approximately ten times greater than the average number for the corresponding holding period from the first. However, despite this, the W-shaped intraday structure that was observed in the overall sample is also prevalent in
each of the two subsamples.

3.2 Intraday volatility

The Garman and Klass volatility estimates shown in the second column of Figure 3 exhibit a broadly similar pattern to that of the average intraday volume. This is not surprising in light of the well-documented relationship between trading volume and volatility in the market microstructure literature.\textsuperscript{13} Moreover, it suggests that the intraday pattern of volume is not simply an artifact of the data source, as suggested above, given that the volatility of the exchange rate should not be affected by the trading systems through which the quotes are recorded. Both the magnitudes and the patterns of intraday volatility are essentially the same over the two subsamples.

In contrast to the intraday W-pattern for volume, the peaks for midrate volatility are more noticeable. The central peak of the pattern, occurring in the 11:00 AM to 12:00 PM holding period, is primarily the result of the scheduled release of Australian macroeconomic announcements at 11:30 AM by the Australian Bureau of Statistics. Furthermore, there is also evidence of a similar peak between 10:00 PM and 11:00 PM, which corresponds to the equivalent scheduled announcements of economic data in the United States. These markedly different peaks around the scheduled announcement time lend credence to our decision to incorporate macroeconomic control variables in Equation 4.

The timing of the volatility peaks observed within our data differs slightly from those found by Hogan and Batten (2005). However, as with volume, the same fundamental tri-peaked pattern exists. One potential source for this difference may be the substantially longer sample period within our study, making it more representative of the market for the AUD.

\textsuperscript{13} Tauchen and Pitts (1983)’s mixture of distribution models explain the positive correlations between trade volume and volatility in equity markets. Admati and Pfleiderer (1988) among others focused more on the role of informed traders in driving this positive relationship. In the foreign exchange markets, the positive relationship is reported by Bollerslev and Domowitz (1993), Goodhart and Figliuoli (1991), Grammatikos and Saunders (1986), Hartmann (1999), Jorion (1996).
3.3 Intraday bid-ask spreads

During the onshore period, the average bid-ask spreads (third column of Figure 3) display a similar but weaker W-shaped pattern to the two variables discussed above. However, the average spread is at its lowest during the New York morning (12:00 AM to 04:00 AM), which approximately corresponds to that segment of the New York trading day where the number of quotes being provided for the USD/AUD is at its highest (see first column of Figure 3). The holding period with the highest average spread occurs immediately after this time, 04:00 AM and 05:00 AM, which forms the first peak of the W-shape intraday pattern for the onshore period. Although evident in both the overall and the first subsample, we note that this spike in the average spread is absent from the second subsample. The co-occurrence of narrow spreads and elevated trading volume in New York morning is largely consistent with Hogan and Batten (2005), Clifton and Plumb (2007) and Poole and D’Arcy (2008).

4. Time series estimations

4.1 The relationship between interventions and intraday AUD volatilities

In this study, the use of an ARMAX model to identify the RBA’s intervention timings does not depend on assumptions about the direction of the causality between the occurrence of interventions and higher market volatility.\textsuperscript{14} We instead recognize that a relationship does exist, and on the basis of the literature (Bein, 2004; Baillie and Osterberg, 1997; Chang and Taylor, 1998; Edison, 2006; Dominguez, 1998; Frenkel et al., 2005, etc.) we are able to form the \textit{a priori} expectation that this relationship is positive in direction. Therefore, we identify the approximate times of the RBA’s interventions on the basis of the magnitude and

\textsuperscript{14}We also investigated the relationship between the trade volume and the bid-ask spread volatility on the one hand and the interventions on the other. The time series regression results are qualitatively similar to the correlation patterns between the volatility and the interventions we report in this section and so they are not reported to save space. Interested readers may obtain these results from the corresponding author.
significance of the intervention coefficient ($b_n$) in Equations 2 and 3. A positive (negative) estimate would be indicative of a positive (negative) correlation between the RBA transaction series and the intradaily AUD volatility after controlling for other potential volatility-inducing factors. The intervention coefficients for the regressions corresponding to each of the twenty-four holding periods in the day for the overall sample are presented in Figure 4. Those significant at 1%, 5% and 10% are shown as black bars, checker board patterned bars, and horizontal lined bars, respectively. The first column displays those coefficients for the intervention variable when specified using the series containing the RBA’s transactions with the market (NMP, the traditionally accepted definition of intervention). The second column presents the coefficients utilizing the series containing RBA’s transactions with the government (NPG). Finally, the third column presents the coefficients for the series that is the NMP net of government related transactions (NMPXG, i.e. calculated as NMP plus NPG, see footnote 7). Panels A, B and C report full, first and second sample results, respectively.

In the first column of Figure 4, we detect several distinct regions of intervention across the intraday horizons for the full sample. First, toward the end of the onshore business period, we observe a highly significant and relatively large coefficient on the intervention variable for the 4PM – 5PM period, surrounded by substantially smaller yet still significant coefficients during both the 2PM – 3PM and 5PM – 6PM holding periods. Second, in holding periods that correspond to the early hours of European and London trading, we observe a cluster of three significant holding periods between 7PM and 10PM that progressively decline in magnitude. Third, we observe a weakly significant (at 10%) holding period in the early hours of New York trade (1AM – 2AM AEST). Finally, we observe a significant

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15It is not practical to present the ARMAX estimation results due to the large number of individual estimations involved. Figure 4 represents a total of 216 separate estimations (24 per graph times 9). We present only the intervention coefficient in these estimations in a summary graph form in Figures 4 and 5.

16The results presented in Figures 4 and 5 represent only those transactions in the original series greater than 100 million AUD in magnitude. The results are substantively similar regardless of the intervention thresholds (greater than 0, 50, 100 and 150 million AUD).
coefficient in the 9AM – 10AM holding period. Each of the significant coefficients identified above display the expected positive contemporaneous relationship. One exception to this is for the holding period at 10AM – 11AM, where we observe a small, negative coefficient that is significant at 5%.

The second column of Figure 4 presents the intervention coefficients when specified according to our enhanced intervention proxy, which attempts to mitigate any influence that the RBA’s transactions with the government may have on the results. We observe broadly the same pattern as in the first column, whereby the RBA appears to intervene late in the onshore period, early in the European offshore period and then again early in the New York offshore period. Utilizing this specification of intervention, we find that those holding periods early in the Australian onshore period (9AM – 11AM AEST) are no longer significant in the first subsample.

The third column presents the intervention coefficients using the transactions conducted between the RBA and the government. There is no significant relationship between these transactions and the AUD volatility at any time of the day.

Panels B and C of Figure 4 respectively present the intervention coefficients from the first and the second subsamples. The first subsample spans a period in which the RBA has publicly acknowledged that they conducted interventions (Reserve Bank of Australia, 2008). For the first sample, results are nearly identical to those of the full sample.

The second subsample is a period in which no intervention occurred and we are able to infer that all transactions recorded in the market series (the traditionally accepted proxy for intervention) must be either transactions made by the RBA in order to cover foreign exchange positions taken from the government or transactions undertaken in order to manage their own liquidity requirements. A positive relationship between these transactions and the market
volatility is not expected to be strong within this subsample, as the RBA states that when rebuilding its foreign currency reserves, it makes use of an agent bank that would allow it to hide its presence and therefore reduce its impact on the market (Becker and Sincalir, 2004; Rankin, 1998). Except for the 9AM – 10AM holding period, we observe in Panel C a broad pattern of insignificant or a negative relationship at these times between non-intervention market transactions and the volatility. It is open to interpretation whether these non-intervention transactions are inadvertently the cause of lower market volatility or whether the RBA simply times their non-intervention transactions to coincide with periods of lower market volatility. In light of the literature that has blamed intervention for causing higher volatility (Bein, 2004; Baillie and Osterberg, 1997; Chang and Taylor, 1998; Edison, 2006; Dominguez, 1998; Frenkel et al., 2005, etc.), the first of these two interpretations would be a rather counterintuitive and ironic finding, were the non-intervention transactions of the RBA to achieve the desired outcome that their intervention counterparts could not. The more intuitive explanation, however, would be that the lower market volatility is a component of the RBA’s reaction function for these non-intervention transactions. One such rationale for this may be that the RBA perceives a stable market as one that is more liquid and better equipped to absorb their transactions. This would suggest that the RBA seeks to minimize the transaction costs associated with these non-intervention transactions by waiting until the periods of low exchange rate volatility.

Moreover, the largest of the significant negative coefficients that we observe in Panels C occur during the early New York trading day (0AM – 1AM and 2AM – 3AM), which corresponds to an intraday period with above average levels of trading volume and the lowest average bid-ask spread (as seen in Figure 3).
4.2 The relationship between interventions and intraday average bid-ask spreads

Figure 5 presents the coefficients of the intervention variable to Equation 3 where the dependent variable for the model is the average bid-ask spreads per holding period. For the whole sample results (shown in Panel A), we observe no significant positive relationship between the average spread per holding period and either the traditionally accepted definition of intervention (first column) or our enhanced proxy for intervention (second column). However, when we examine the relationship between the average spread and the transactions that the RBA conducts with the government (third column), we observe a number of significant negative coefficients across the 24-hour horizon. As these transactions are government driven and are not reflected in either of the market series, we are able to infer some limited causality such that this general pattern results from the government’s desire to minimize their own transaction costs when dealing with the RBA for their foreign exchange needs.

The first sample analyses shown in panel B also show no significant relationship between either of our two intervention proxies and the average spread except for several of the significant coefficients (one positive and one negative, both at 10%) for the overall intervention variables. However, the RBA transactions with the government show a total of 9 significant (all negative) hourly correlations with the bid-ask spreads.

During the second subsample (Panel C), we not only observe significant negative coefficients in transactions between the RBA and the government, but also one large and significant coefficient in the holding period at 4AM – 5AM for the specification of the intervention variable that makes use of RBA transactions with the market. We also observe a similar pattern of negative coefficients in the second and the third column. As we know that no interventions occurred within this subsample, our enhanced proxy for intervention (second column) seems likely to be capturing the effect of the RBA’s transactions with the
government. As discussed previously, the formation of the net series from the market and government series results in an increase in the number of observations over that contained within the market-only transaction series, leading to this effect.

The most important finding from the second subsample is the significant negative relationship between the average spread and the government’s transactions with the RBA during the New York trading day (post-midnight, AEST). When obtaining foreign currency from the RBA in order to conduct its operations abroad, the government would seek to minimize the cost to the taxpayer of acquiring these funds. The pattern we observe indicates an inclination for these transactions to be undertaken in the period prior to Australian onshore trading hours, which also corresponds to that period of the intraday horizon where the bid-ask spread has tended to be at its lowest (see Figure 3). As noted, we are able to infer that lower average spreads in the USD/AUD rate lead to the transactions between the RBA and the government. The reverse causal inference may not be possible as these transactions do not occur within the market, but rather are private between the government and the RBA. If the RBA were to immediately offset these government transactions within the market, we would expect to observe a similar pattern in both second and the third columns of Figure 5. However, we do not observe such a pattern.

5. Conclusion
We report several important empirical findings that contribute to the literature on central bank intervention. First, we provide a detailed analysis of the intraday USD/AUD market that is the setting for interventions by the Reserve Bank of Australia. Through the use of one hour holding periods assembled from high frequency tick by tick quote data, we provide insights into the patterns of intraday AUD/USD market activities. Our findings are generally congruent with the microstructure literature, whereby the uncertainty that exists at the
beginning and end of each trading day is reflected in higher exchange rate volatility and wider bid-ask spreads (see Admiti and Pfleidrerer, 1988; Clifton and Plumb, 2007; Hartmann, 1999; Poole and D’Arcy, 2008, etc.). The volume of quotes was found to follow a similar intraday pattern to that of volatility, with a higher frequency of trades and a greater degree of price discovery occurring outside of the Australian onshore market. In addition, we observe abnormal spikes in volatility and trading volume surrounding the time of macroeconomic announcements in both Australia and the United States, which we control for in our main empirical estimations.

Second, this research is the first study to use high frequency data and report approximate market intraday timing of the RBA’s interventions. Furthermore, we make use of newly available government transaction data that allow us to isolate and partially mitigate the impact that such non-intervention transactions may have on the traditional intervention proxy. We find that the RBA tends to intervene late in the onshore business period, early in the London or European business hours and again early in New York trading hours, and that these results are robust to multiple specifications of what constitutes an intervention. We conjecture that the RBA intervenes at these specific times in order to provide new information to the traders commencing their shifts in both London and New York, who would then act on that information and move the exchange rate in the direction desired by the RBA. Moreover, as these interventions correspond to periods of higher volatility, we propose that interventions are conducted at these times in order to reduce short-term volatility at the market opening, thereby setting a trend for the remainder of the trading day.

Finally, we find a negative contemporaneous correlation between the RBA’s non-intervention transactions in the market and the volatility of the exchange rate at various periods of the day. This is conjectured to be the result of the negative relationship between price volatility and the depth of the market at any given bid and ask level, thereby affording
the RBA some confidence that these non-intervention transactions are likely to have little impact on the exchange rate. As the RBA has stated that it often transacts in secrecy through agent banks in order to limit the market impact of these non-intervention transactions, we are able to infer some limited degree of causality, such that the volatility of the exchange rate at these times is a component of the RBA’s reaction function for these transactions. Furthermore, we observe a negative relationship in our second subsample between the average bid-ask spread during the New York trading period and the transactions that the RBA undertakes with the government. As these transactions are conducted privately, whereas the bid-ask spread is a market-driven factor, we are likewise able to infer that the government chooses to transact with the RBA when it is able to minimize the cost of doing so (as measured by the magnitude of the bid-ask spread), as the reverse causal inference is not possible.

In short, our findings have important policy implications in the way of suggesting potentially optimal timing of intervention by the RBA. In addition, there are important implications for other market participants, as trading against monetary authorities having been shown to be a potentially lucrative endeavor (Sweeney, 1997; Szakmary and Mathur, 1997). Hedge funds and other active traders in the USD/AUD market would find value in knowing the general timing of interventions by the Reserve Bank of Australia.
References


Table 1: Descriptive Statistics of the RBA’s Intervention Series

<table>
<thead>
<tr>
<th></th>
<th>Transactions with Market (NMP)</th>
<th>Transactions with Government and other parties (NPG)</th>
<th>Transactions with Market Net of Transactions with Government (NMPXG)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency of transactions (No. of Days)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purchase of AUD</td>
<td>53</td>
<td>1929</td>
<td>1515</td>
</tr>
<tr>
<td>(% of business days)</td>
<td>1.85%</td>
<td>67.26%</td>
<td>52.82%</td>
</tr>
<tr>
<td>Sale of AUD</td>
<td>971</td>
<td>727</td>
<td>1183</td>
</tr>
<tr>
<td>(% of business days)</td>
<td>33.86%</td>
<td>25.35%</td>
<td>41.25%</td>
</tr>
<tr>
<td>Total</td>
<td>1024</td>
<td>2656</td>
<td>2698</td>
</tr>
<tr>
<td>(% of business days)</td>
<td>35.70%</td>
<td>92.61%</td>
<td>94.07%</td>
</tr>
<tr>
<td><strong>Magnitude of transactions (AUD)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Absolute Transaction</td>
<td>47.1</td>
<td>26.2</td>
<td>33.5</td>
</tr>
<tr>
<td>Average buy of AUD</td>
<td>154.8</td>
<td>25.3</td>
<td>28.5</td>
</tr>
<tr>
<td>Average sell of AUD</td>
<td>41.2</td>
<td>28.8</td>
<td>39.8</td>
</tr>
<tr>
<td>Maximum buy of AUD</td>
<td>1188.5</td>
<td>698.9</td>
<td>1198.9</td>
</tr>
<tr>
<td>Maximum sell of AUD</td>
<td>376.0</td>
<td>477.2</td>
<td>590.4</td>
</tr>
</tbody>
</table>

**Subsample I (01 January 1996 – 31 December 2001)**

|                           |                               |                                                      |                                                                  |
| Frequency of transactions (No. of Days) |                               |                                                      |                                                                  |
| Purchase of AUD           | 53                            | 1157                                                 | 1021                                                             |
| (% of business days)      | 3.39%                         | 73.98%                                               | 65.28%                                                           |
| Sale of AUD               | 303                           | 302                                                  | 452                                                              |
| (% of business days)      | 19.37%                        | 19.31%                                               | 28.90%                                                           |
| Total                     | 356                           | 1459                                                 | 1473                                                             |
| (% of business days)      | 22.76%                        | 93.29%                                               | 94.18%                                                           |
| **Magnitude of transactions (AUD)** |                               |                                                      |                                                                  |
| Average Absolute Transaction | 58.3                         | 25.3                                                 | 34.7                                                             |
| Average buy of AUD        | 154.8                         | 23.5                                                 | 31.5                                                             |
| Average sell of AUD       | 41.4                          | 31.9                                                 | 41.9                                                             |
| Maximum buy of AUD        | 1188.5                        | 698.9                                                | 1198.9                                                           |
| Maximum sell of AUD       | 285.7                         | 477.2                                                | 477.2                                                            |

**Subsample II (01 January 2002 – 29 December 2006)**

|                           |                               |                                                      |                                                                  |
| Frequency of transactions (No. of Days) |                               |                                                      |                                                                  |
| Purchase of AUD           | 0                             | 772                                                  | 494                                                              |
| (% of business days)      | 0.00%                         | 59.20%                                               | 37.88%                                                           |
| Sale of AUD               | 668                           | 425                                                  | 731                                                              |
| (% of business days)      | 51.23%                        | 32.59%                                               | 56.06%                                                           |
| Total                     | 668                           | 1197                                                 | 1225                                                             |
| (% of business days)      | 51.23%                        | 91.79%                                               | 93.94%                                                           |
| **Magnitude of transactions (AUD)** |                               |                                                      |                                                                  |
| Average Absolute Transaction | 41.1                         | 27.4                                                 | 32.0                                                             |
| Average buy of AUD        | 0.0                           | 27.9                                                 | 22.3                                                             |
| Average sell of AUD       | 41.1                          | 26.5                                                 | 38.5                                                             |
| Maximum buy of AUD        | 0                             | 408                                                  | 390.3                                                            |
| Maximum sell of AUD       | 376.0                         | 439.7                                                | 590.4                                                            |
Figure 1: USD/AUD exchange rate and RBA transactions

**Panel B: Net Market Purchases of Foreign Currency by RBA (NMP)**

**Panel C: Net Purchases of Foreign Currency from Government (NPG)**

**Panel D: Net Market Purchases Excluding Government Transactions (NMPXG)**

**Subsample I**
- Intervention Period
- 03-01-1996 to 31-12-2001

**Subsample II**
- No Intervention Period
- 01-01-2002 to 29-12-2006
**Figure 2: Construction of hourly USD/AUD market characteristics**

The figure below graphically presents the processing of the tick-by-tick foreign exchange quote data into holding periods of one hour in length. Each of the 24 time series (columns) represents a cross section of the sample that corresponds to the same time interval on each of the 2,868 trading days of the sample (rows). The variable that each of the time series below represents is the Garman and Klass volatility of the midrate and spread. However, corresponding time series are likewise calculated for both volume and average spread.

<table>
<thead>
<tr>
<th>Intraday Time Horizon</th>
<th>00:00:00–23:59:59</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Series 1</td>
<td>00:00–00:59:59</td>
</tr>
<tr>
<td>Time Series 2</td>
<td>01:00–01:59:59</td>
</tr>
<tr>
<td>Time Series n</td>
<td>02:00–22:59:59</td>
</tr>
<tr>
<td>Time Series 23</td>
<td>22:00–22:59:59</td>
</tr>
<tr>
<td>Time Series 24</td>
<td>23:00–23:59:59</td>
</tr>
</tbody>
</table>

Day 1

\[
\hat{\sigma}^2_{(GK);1,1} \quad \hat{\sigma}^2_{(GK);1,2} \quad \hat{\sigma}^2_{(GK);1,n} \quad \hat{\sigma}^2_{(GK);1,23} \quad \hat{\sigma}^2_{(GK);1,24}
\]

Day 2

\[
\hat{\sigma}^2_{(GK);2,1} \quad \hat{\sigma}^2_{(GK);2,2} \quad \hat{\sigma}^2_{(GK);2,n} \quad \hat{\sigma}^2_{(GK);2,23} \quad \hat{\sigma}^2_{(GK);2,24}
\]

Day t

\[
\hat{\sigma}^2_{(GK);t,1} \quad \hat{\sigma}^2_{(GK);t,2} \quad \hat{\sigma}^2_{(GK);t,n} \quad \hat{\sigma}^2_{(GK);t,23} \quad \hat{\sigma}^2_{(GK);t,24}
\]

Day 2,867

\[
\hat{\sigma}^2_{(GK);2867,1} \quad \hat{\sigma}^2_{(GK);2867,2} \quad \hat{\sigma}^2_{(GK);2867,n} \quad \hat{\sigma}^2_{(GK);2867,23} \quad \hat{\sigma}^2_{(GK);2867,24}
\]

Day 2,868

\[
\hat{\sigma}^2_{(GK);2868,1} \quad \hat{\sigma}^2_{(GK);2868,2} \quad \hat{\sigma}^2_{(GK);2868,n} \quad \hat{\sigma}^2_{(GK);2868,23} \quad \hat{\sigma}^2_{(GK);2868,24}
\]
Figure 3: Plots of volume, volatility and bid-ask spreads over 24-hour period

Average Volume of Quotes

Average GK Volatility of Midrate

Panel A: Full Sample, 03-Jan-1996 to 29-Dec-2006

Panel B: Sample 1, 03-Jan-1996 to 31-Dec-2001

Panel C: Sample 2, 02-Jan-2002 to 29-Dec-2006

Average Bid-Ask Spread
Figure 4: Coefficients of Intervention variable for the G-K volatility models

Transaction with market (NMP)

Transaction with market net of government (NMPXG)
Panel A: Full Sample, 03-Jan-1996 to 29-Dec-2006

Panel B: Sample 1, 03-Jan-1996 to 31-Dec-2001

Panel C: Sample 2, 02-Jan-2002 to 29-Dec-2006

Transaction with government (NPG)
Figure 5: Coefficients of Intervention variable for the average spread models

Transaction with market (NMP)

Panel A: Full Sample, 03-Jan-1996 to 29-Dec-2006

Panel B: Sample 1, 03-Jan-1996 to 31-Dec-2001

Panel C: Sample 2, 02-Jan-2002 to 29-Dec-2006

Transaction with market net of government (NMPX)

Transaction with government (NPG)