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"Trading Activity and Foreign Exchange Market Quality"

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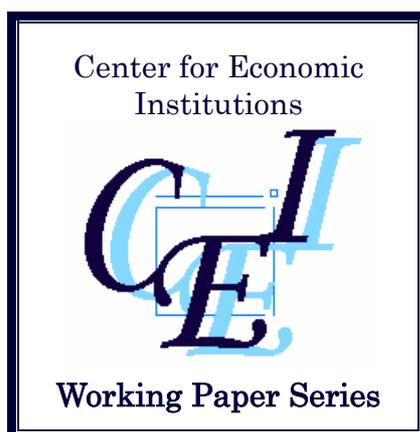
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Trading Activity and Foreign Exchange Market Quality[*]

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Abstract

This paper studies intraday market quality for currency pairs with very different trading characteristics, the Euro-U.S. dollar and the Canadian dollar-U.S. dollar. Two sets of tests—the first based on the ratio of long term to short term variances, and the second based on information spillovers—provide consistent conclusions regarding market quality. The variance ratio analysis shows that market quality is highest for the Euro during European trading and lowest during Asian trading. For the Canadian dollar, market quality is highest during North American trading and lowest during Asian trading. Analysis of information spillovers shows that innovations in returns and volatility for the more heavily-traded Euro predict returns and volatility for the Canadian dollar during Asian and European trading, but innovations for the dollar have predictive power for the Euro during North American trading. Our results suggest that foreign exchange market quality is high, not always when quoting and trading activity are heavy but rather, and somewhat unexpectedly, when activity is not only high, but also geographically focused and concentrated among a limited number of major dealers.

Trading Activity and Foreign Exchange Market Quality

Abstract

This paper studies intraday currency market quality for currency pairs with very different trading characteristics, the Euro-U.S. dollar and the Canadian dollar-U.S. dollar. Two sets of tests—the first based on the ratio of long term to short term variances, and the second based on information spillovers—provide consistent conclusions regarding market quality. The variance ratio analysis shows that market quality is highest for the Euro during European trading and lowest during Asian trading. For the Canadian dollar, market quality is highest during North American trading and lowest during Asian trading. Analysis of information spillovers shows that innovations in returns and volatility for the more heavily-traded Euro predict returns and volatility for the Canadian dollar during Asian and European trading, but innovations for the dollar have predictive power for the Euro during North American trading. Our results suggest that foreign exchange market quality is high, not always when quoting and trading activity are heavy but rather, and somewhat unexpectedly, when activity is not only high, but also geographically focused and concentrated among a limited number of major dealers.

1. Introduction

Market quality is a multi-dimensional notion intended to describe the speed and accuracy with which new price relevant information is impounded in prices. A high quality market is one in which prices quickly and accurately reflect new information. Despite its status as the largest financial market in the world, the quality of the foreign exchange market has not been studied extensively[1]. In this paper, we analyze foreign exchange market quality for two currency pairs with very different levels of and geographic patterns in trading activity, the Euro-U.S. dollar and the Canadian dollar-U.S. dollar. This allows us to focus on the link between currency market quality and the level of trading, regarded as a key determinant of market quality.

Our initial tests employ a measure of market quality based on transitory volatility. In a high quality market, price changes should be permanent and transitory volatility low, so the ratio of (scaled) long-term variance to short-term return variance should be close to 1.0 throughout the trading day.[2] The second set of tests focuses on the transmission of information across currencies. If the incorporation of common information becomes more rapid and accurate as market quality increases, price changes for the currency with higher quality will lead those for the currency with lower quality. We use a GARCH framework to investigate return and volatility spillovers between our currency pairs over the trading day.

We choose the Euro-U.S. dollar and the Canadian dollar-U.S. dollar currency pairs because of the differences in their levels of, and intraday patterns in, trading activity. The Euro-U.S. dollar (henceforth, the Euro) is the most heavily traded currency pair and is actively traded throughout the day. The Canadian dollar-U.S. dollar (henceforth, the Canadian dollar) is considerably less

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[1] Notable exceptions are Ito, Lyons and Melvin (1999) and Andersen, Bollerslev and Das (2001), which have studied aspects of market quality for one currency (the yen) around a specific event. For a general survey of the market quality literature, see Harris (2003).

[2] For a discussion, see Lo and MacKinlay (1988) or Bessembinder (2003).

actively traded, and its trading is concentrated in North America.[3] There are also differences in the

number and timing of announcements relevant to each currency. For instance, both currency pairs

will be affected by important U.S. economic announcements, which occur at 8:30 am (EST). In

addition, while the Euro will be impacted by announcements from the major European countries,

the Canadian dollar will be impacted by Canadian announcements. Our analysis of intraday market

quality captures the effects of these regularly scheduled events[4].

The sample period for our analysis is the calendar year 2000. We start by examining

proxies for trading activity and information arrival—quoting intensity and return volatility—for

each currency over the trading day. For the Euro, quoting intensity and volatility increase very

rapidly as the European markets open; both increase further as the North American markets open

and then stabilize until the European markets close, after which they decline significantly. For the

Canadian dollar, quoting frequency and volatility are low during Asian trading and increase when

the European markets open, but the most significant increase occurs when the North American

markets open. Activity in the Canadian dollar peaks during the overlap in European and North

American trading and remains relatively high until the close of the North American markets.

These results suggest that trading and information arrival for the Euro are more evenly spread out

across European and North American trading while those for the Canadian dollar are more heavily

concentrated in North America.

Turning to market quality, the variance ratio for the Canadian dollar, while more variable

than that for the Euro, is, somewhat surprisingly, closer to 1.0 over the entire day. This suggests

that market quality is higher for the less heavily traded Canadian dollar than for the Euro. Over the

trading day, the variance ratio is closest to 1.0 for the Canadian dollar during North American

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[3] BIS (2004) statistics show that the Euro-U.S. dollar currency pair is involved in approximately 28% of all foreign exchange transactions and actively traded around the globe. The Canadian dollar-U.S. dollar is the sixth most actively traded currency pair, accounting for roughly 4% of all transactions, and has over two-thirds of its trading volume in North America.

trading, whereas it is closest to 1.0 for the Euro during European-only trading. Thus, market quality for the Canadian dollar is highest when the dollar is most actively traded, but market quality for the Euro declines slightly as trading activity peaks during joint trading in Europe and North America.

There are at least two explanations for this unexpected difference across the currencies. The larger volume of announcements relevant to the Euro (i.e. announcements in several European countries and the U.S.) relative to the Canadian dollar could induce greater noise in Euro prices. A more intriguing explanation consistent with both the level of, and the intraday pattern in, the variance ratios is based on geographic variations in the number of major dealers for the Euro and the Canadian dollar.

The Euro is traded by a larger number of dealers than the Canadian dollar over the trading day (e.g. BIS, 2001, 2004), so there is less concentrated price discovery for the Euro. We study the number of quoting dealers over the trading day for the Deutsche Mark (an actively–traded currency like the Euro) and for the Canadian dollar. Quoting activity for the more actively-traded Deutsche Mark is most concentrated among dealers during European-only trading, because both European dealers and dealers from other regions (e.g. North America) are active participants in the market at other times. For the Canadian dollar, quoting activity outside North American hours is spread across a number of regional dealers and the foreign branches of some North American banks. However, quoting activity transfers to two major North American banks during North American trading, and this leads to more concentrated price discovery at this time.

The above explanation extends Evans (2002) and Evans and Lyons (2002), who find that order flow related information is more rapidly incorporated into prices as trading activity increases; at the same time, however, prices become noisier because the amount of private information

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[4] Because of the large number of announcements, we do not consider individual announcements, but capture their effects through level and interactive dummies that correspond to the timing of these announcements.

increases and inventory pressures become more acute. Our results suggest that noise increases with quoting activity when the number of dealers simultaneously quoting the currency increases.

The second phase of our analysis investigates market quality from the perspective of information transmission between the currency pairs. We estimate a GARCH model that measures return and volatility spillovers between the currencies over the trading day (similar in spirit to studies such as Baillie and Bollerslev (1990) and Engle et al. (1990)). The existence of spillovers suggests that one currency incorporates common information before the other

Information appears to flow from the Euro to the Canadian dollar during Asian trading, when the variance ratio test shows Canadian dollar market quality to be low, and from the Canadian dollar to the Euro during the overlap in European and North American trading, when Canadian dollar market quality is higher than for the Euro. Additionally, there are bi-directional spillovers during market openings, when market quality for both currencies is highest. Somewhat surprisingly, information flows from the Canadian dollar to the Euro during European trading, when Euro market quality is higher than for the Canadian dollar. On the whole, however, the GARCH analysis paints a similar picture of market quality to the variance ratio tests.

Our analysis suggests that market quality depends on factors beyond the level of trading activity. Factors such as dealer concentration and the geographic dispersion of trading activity also play a significant role in explaining market quality. An additional contribution of our paper is its characterization of the market microstructure and market quality of a less actively traded currency. Even though a growing portion of trading now involves less liquid currencies such as the Canadian and Australian dollars versus the U.S. dollar the microstructure of these currency pairs remains largely unexplored.[5].

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[5] Studies starting with Goodhart and Figliouli (1991) and Bollerslev and Domowitz (1993) and continuing up to the comprehensive survey of Dacrogna et al. (2001) only briefly discuss less actively traded currencies.

The paper develops as follows. Section two provides a description of the data. Section three describes our empirical techniques and the results of our formal analysis. Section four concludes.

2. Data

Our data consist of intraday indicative quotes from the Canadian dollar and Euro spot markets. The data cover the 12-month period, January 1, 2000 through December 31, 2000 and are provided by Olsen and Associates. As in other studies (e.g., Bollerslev and Domowitz (1993)), we exclude weekends and holidays, because these are characterized by low and inconsistent levels of trading activity. We define the weekend as extending from 20:00 GMT Friday evening (the close of the North American markets) until 23:59 GMT Sunday evening (when trading commences in the Far East), and holidays for the Euro (Canadian dollar) as days on which the stock exchange in either London (Toronto) or New York is closed.

In our analysis, we divide the 24-hour day into five geographic regions to capture the well-documented differences in activity as trading moves from the Asian markets to the European and then the North American markets (e.g., see Bollerslev and Domowitz (1993) and Huang and Masulis (1999)). As in prior studies, we define Asian trading hours as 00:00-08:00 GMT, European-only trading hours as 08:00-12:00, the overlap in European and North American trading as 12:00-16:00, North American-only trading hours as 16:00-20:00, and post-North American trading as 20:00-24:00[6].

Our tests require equally spaced observations, so we report results based on 15-minute measurement intervals. We choose 15-minute intervals to mitigate concerns associated with the use of very high frequency indicative quotes while still being able to capture the rapidly changing

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[6] A time line of the opening and closing hours for each geographic region is provided in Figure 1. In the foreign currency market, unlike the equity markets, there is no formal opening or closing of the major markets. The changes in activity associated with the opening and closing of each market occur over a period of roughly one hour around the indicated times.

features of intraday trading behavior (see Dacrogna et al. (2001) for a thorough discussion). Our choice of 15-minute intervals is consistent with Goodhart, Ito and Payne (1996) and Danielsson and Payne (2002) who show that at coarser frequencies (i.e. when the measurement interval is greater than 10 minutes in length) indicative quote data and actual transaction data have similar characteristics.[7]

For our analysis, we focus on the following variables constructed from the indicative quote data.

Number of quotes. A frequently used proxy for trading activity and the rate of information arrival is the total number of valid quotes submitted in each interval during the day (in our case, in each 15-minute interval). Recent studies have cast doubt on the reliability of quoting frequency as a proxy for trading activity in the Euro (e.g., Hau, Killeen and Moore (2002)); yet, quoting frequency is the best available proxy for trading volume and is widely–used (see Bollerslev and Domowitz (1993), Hartmann (1998) and Evans (2002), for instance). Further, Melvin and Yin (2000) present evidence that quoting frequency measures the rate at which information is incorporated into prices. To study the relation between market quality and trading activity, we consider the link between market quality and quoting frequency. Existing studies do not agree on whether market quality increases or decreases as the level of activity changes (Bessembinder (2003) provides a nice survey of these arguments). We measure market quality across the trading day and investigate how it changes with quoting frequency for the two currency pairs.

Returns and return volatility. Returns and return volatility are used to measure information arrival and its incorporation into prices. We calculate midpoint returns using the last valid quote submitted in each 15-minute interval. To measure high frequency information arrival, we compute the unconditional variance of the returns for each 15-minute interval (e.g. Ross (1988) or

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[7] We also consider 30-minute and 60-minute intervals and our conclusions are qualitatively similar, so these results are not presented.

Danielsson and Payne (2002)). An increase in the rate of information arrival should be associated with larger price changes and hence with higher return variability. To study market quality, we calculate the ratio of unconditional return variances over longer and short horizons (the details are in section 3.2). If information is efficiently incorporated into prices, the ratio of the (appropriately scaled) long-term variance to short-term variance will be close to 1.0. Finally, we use the returns in a GARCH model (described in Section 3.3) to capture cross-market and cross-currency information spillovers. Information spillovers across markets and currencies will occur if one currency incorporates news into prices more quickly than the other.

Although studies of market quality often include quoted bid-ask spreads, we do not consider spreads both because spreads tend to cluster on certain discrete values (e.g. Bollerslev and Melvin (1994)), and because spreads vary with trade quantity (e.g. Hasbrouck (1991a, 1991b and 1999)) and counterparty identity (e.g. Osler (2005)), neither of which is available to us.

3. Results

3.1. Descriptive statistics

We start by summarizing the major qualitative features of our data. Since some of these have been documented elsewhere in the literature, we focus on the features that are either less familiar or more important for our study.

3.1.1. Quoting frequency

Figure 2 presents 15-minute averages of quoting frequency for each currency, computed across the entire year of data. The left hand axis refers to the Euro, while the right hand axis refers to the Canadian dollar. Quoting frequency for the Euro is relatively low (less than 200 quotes per hour) until the opening of the markets in Europe (at 7:00 GMT), but increases rapidly to over 1,500 quotes per hour by 10:00 GMT. The number of quotes remains high throughout European trading, declines gradually as the markets in Europe close (between 15:00 and 16:00 GMT), declines

further at 18:00 GMT, and is less than 100 quotes per hour by the time the North American markets close at 20:00 GMT.

The number of quotes for the Canadian dollar is approximately 1/20th that for the Euro. Quoting frequency is very low before the opening of the European markets (below 20 quotes per hour), but rises to almost 50 quotes per hour during morning trading in Europe. Quoting activity increases dramatically (more than doubling) with the opening of the markets in North America at 12:00 GMT, reaching a peak of almost 180 quotes per hour while both the European and North American markets are open. Although the close of the European markets is, as with the Euro, associated with a drop in quoting activity for the Canadian dollar, the decline is much slower than for the Euro. The fact that the most intense quoting activity occurs during North American trading is consistent with trading for the Canadian dollar being geographically concentrated.

Comparing the mean number of quotes for the currencies over the trading day, it is evident both that the Canadian dollar is considerably less actively traded than the Euro, and that both series display substantial variation. These differences in quoting activity raise the possibility of intraday differences in the speed and accuracy with which information is incorporated into the prices of the two currencies. If, for example, the common belief that market quality is directly related to the level of trading activity is true, the Euro should incorporate information more quickly than the more thinly traded Canadian dollar throughout the day. However, this disparity in the speed of adjustment should decrease as trading activity in the Canadian dollar increases with the opening of the North American markets.

3.1.2. Return volatility

To investigate the patterns in information arrival over the trading day, Figure 3 plots return variability in each 15-minute interval. Volatility for the Euro is low during Asian trading but increases sharply as the European markets open, and peaks once the European markets are fully operational at 8:00 GMT. There is another, albeit more muted, spike in volatility when the North American markets open, and volatility drops smoothly from the close of European trading until the

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end of trading in North America. For the Canadian dollar, return volatility is low through Asian trading but increases gradually as the European markets open. We see an especially strong increase in volatility just before, and during, the opening of the North American markets, after which the volatility declines in much the same way as for the Euro.

The spikes in volatility for both currency pairs accompanying the opening and closing of major markets give rise to several U-shaped curves. These patterns in volatility are consistent with models such as Admati and Pfleiderer (1988) and Brock and Kleidon (1992), as well as with experimental evidence in Bloomfield, O'Hara and Saar (2005) and empirical evidence in Lo and Sapp (2005), all of which suggest that informed and uninformed traders concentrate their activity around market openings and closings. This concentration results in heightened information flow at these times.

To summarize, our preliminary analysis shows that quoting behavior and return volatility for the Euro and Canadian dollar differ from each other and change across the trading day. The next two sections more formally explore the relation between these quoting patterns and market quality.

3.2. Variance Ratio Tests of Market Quality

Prices in a high quality market will accurately impound all relevant information, and therefore will neither over- nor under-react. To measure over- or under-reaction, we follow Lo and MacKinlay (1988) and construct the ratio of variances over longer horizons (60 minutes or 30 minutes) and short horizons (15 minutes, the smallest measurement interval in our data). Consider the ratio of the variance of 60-minute returns to four times the variance of 15-minute returns:

$$VR_{hourly} = \frac{Var(R_{60})}{4Var(R_{15})} \tag{1}$$

where R_{60} and R_{15} are 60-minute and 15-minute returns respectively. If exchange rates impound information efficiently, 15-minute changes in exchange rates will be permanent and VR_{hourly} will be

1.0. If exchange rates over-react to information or to order flow, currency prices will eventually display reversion. To the extent that the correction occurs within 60 minutes, this will dampen $Var(R_{60})$ and cause VR_{hourly} to be less than 1.0^8. Possible explanations for excessive short-term price movements are inventory pressures or low liquidity. Similarly, VR_{hourly} will be above 1.0 if exchange rates under-react to information. Market quality will, therefore, be high if VR_{hourly} is close to 1.0, and low otherwise.[9]

Besides VR_{hourly}, we compute an alternative variance ratio using 30-minute and 15-minute returns to investigate whether adjustment occurs more quickly than over 60 minutes:

$$VR_{semi-hourly} = \frac{Var(R_{30})}{2Var(R_{15})} \qquad (2)$$

where R_{30} and R_{15} are the returns for 30-minute and 15-minute intervals. Both variance ratios are computed for each hour in the day to give us 24 variance ratios. We determine whether the variance ratios are significantly different from 1.0 by adapting the formula for the standard error in Lo and MacKinlay (1988, equation 20).[10]

The results for $VR_{semi-hourly}$ and VR_{hourly} are presented in Table 1. We focus our discussion on the results for the VR_{hourly}. The hourly variance ratio for the Euro is significantly less than 1.0 (averages about 0.83) during Asian trading, consistent with over-reaction. It jumps to a level indistinguishable from 1.0 at the opening of the European markets and remains at this level until after lunch in Europe (14:00 GMT). The value of VR_{hourly} is approximately 0.90 (significantly less than 1.0) for much of the rest of European and North American trading. Somewhat surprisingly,

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[8] It is important that the measurement interval for the short-term variance be short enough to capture price distortions, while the long-term variance allow enough time for the distortions to be corrected. We use the 15-minute return as the short-term return because 15-minute intervals abstract from problems associated with using indicative quotes at too high a frequency (see Andersen, Bollerslev and Das (2001) or Dacrogna et al. (2001) for a discussion). We assume that distortions will be corrected within 60 minutes.

[9] French and Roll (1986) and Lo and MacKinlay (1988) examine stock market return autocorrelations using variance ratios and Bessembinder (2003) uses variance ratio tests to study changes in equity market quality.

[10] Lo and MacKinlay (1988, section 1.2) show that the asymptotic distribution of the variance ratio is standard normal under fairly general assumptions and derive the standard error of this distribution.

the ratio is closest to 1.0, not during the period when both European and North American traders are active, but during European-only trading. While the pattern in $VR_{semi\text{-}hourly}$ yields similar conclusions, the values of VR_{hourly} are closer to 1.0, indicating that half-hourly variances do not reflect a complete correction of the noise present in 15-minute returns.

The hourly variance ratio for the Canadian dollar is also below 1.0 during Asian trading, averaging approximately 0.85 and hitting its lowest point, 0.68, at around 4:00 GMT. VR_{hourly} increases gradually as European trading picks up, and is indistinguishable from 1.0 by 11:00 GMT. It remains at this level for most of the remainder of European and North American trading, but declines to values significantly below 1.0 after the close of the North American markets. The values of $VR_{semi\text{-}hourly}$ yield similar conclusions, but these values are, as with the Euro, further below 1.0. Thus, the noise in 15-minute Canadian dollar prices also requires more than 30 minutes to be eliminated.

Interpreting the results, we see that, although the variance ratios for the Euro are more stable over the trading day, they are not closer to 1.0 than those for the Canadian dollar. Thus, on the basis of this statistic, the heavily traded Euro does not display higher market quality than the much more thinly traded Canadian dollar. Additionally, the variance ratios for the Euro are not closer to 1.0 when the Euro is most actively traded. The Canadian dollar, on the other hand, is characterized by increased market quality as it becomes more actively traded.

There are several possible explanations for this somewhat surprising result. First, the greater information flow and larger volume of announcements (in several European countries and the U.S.) for the Euro relative to the Canadian dollar could make prices of the Euro noisier than prices of the Canadian dollar. A second and more intriguing possibility is that there are differences in the nature of order flow over the trading day. This possibility is examined in the following subsection.

3.2.1 Quoter Identities and Locations

We probe these results by studying two auxiliary datasets, also provided by Olsen and Associates, the Deutsche Mark (DM)-U.S. dollar for October 1, 1992 through September 30, 1993, and the Canadian dollar-U.S. dollar for January 1 through December 31, 1995. Though the time frames differ from that of our primary data set, the attractive feature of these datasets is that they contain the identity and location of the dealer placing each quote. We use the DM-U.S. dollar as a proxy for the Euro-U.S. dollar, which only started trading in January 1999.[11]

The intraday patterns in the identity of the quoting dealer and their nation of origin can be seen in Figure 4. In Figure 4a, we consider the percentage of all quotes for the Canadian dollar that originate from dealers in each of the major markets/countries. It is clear that the Canadian dollar is thoroughly dominated by quotes originating from dealers located in Canada. Although many quotes originate from the UK before the North American markets open, quoting activity moves rapidly to Canada once the North American markets open. This is consistent with trading activity in the Canadian dollar being concentrated in the domestic market (e.g. BIS (2004)). Figure 4b shows that two dealers dominate quoting activity in the Canadian dollar during North American trading, each posting more than twice as many quotes as their nearest rivals. It seems reasonable to view these dealers as price leaders and to assume that they capture a sizable fraction of order flow. As a result of this concentration in quoting activity and order flow, we would expect to see an increase in market quality at these times.

Turning to the DM, we see far less dominance in this market. Figure 4c, which summarizes the percentage of quotes by originating country, shows that the UK is the dominant source of these quotes. This is not surprising given its central role in the foreign exchange market (e.g. BIS (2004)). A large number of quotes also originate from other European countries. Quoting activity from U.S.-based dealers is seen to increase between 11:00 and 12:00 (GMT).

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[11] Because Olsen no longer collects quoter identities, we were obliged to employ older data for this analysis, and to study the DM instead of the Euro.

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Given the number of active dealers at this time, quoting activity is impacted by private information and inventory pressures on both sides of the Atlantic to a greater extent than at other times in the day. This is likely to impair market quality for the DM after 12:00 (GMT).

Paralleling our analysis for the Canadian dollar, we consider the proportion of quotes submitted by individual dealers for the DM. Figure 4d shows that Deutsche Bank is a major player in this market. As discussed in studies such as Peiers (1997), and Sapp (2002) this dominant position leads DB to play a price leadership role in the DM market. At about 12:00 (GMT), DB starts to lose its leadership role as major U.S. banks enter the market. The loss of a clear market leader is consistent with our findings that market quality for the Euro decreases as the North American markets open.

We caution that trading patterns for the Canadian dollar might have changed over time and that trading patterns for the DM and Euro might be different. However, historical studies of the foreign exchange market such as BIS (2004) indicate relative stability over time in market share across countries and major dealers. Thus, we believe that this analysis provides insights into how concentration in quoting activity across dealers and countries might impact our results.

Specifically, quoting activity for an actively–traded currency such as the Euro is spread across a large number of geographically dispersed dealers, particularly at times when more than one major market is open. Hence, market quality is impaired by a combination of dispersed private information and inventory effects resulting from fragmented order submissions. By contrast, quoting activity for a less actively–traded currency such as the Canadian dollar is confined to a handful of major dealers, especially when the home market, North America, is open. The resulting centralization in order flow and concentration in price discovery causes market quality to be high.

Overall, therefore, the variance ratio results are broadly consistent with geographic differences in the nature of order flow and in the concentration of dealer activity for the currency pairs. These results suggest that the efficiency with which information is incorporated into prices depends on, not only the level of trading activity, but also its concentration across dealers.

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3.3. GARCH Analysis

The results from the previous section suggest that market quality varies over the trading day for both the Canadian dollar and the Euro. In this section, we study market quality from the perspective of information transmission across currencies. This analysis sheds light on the speed with which common information is impounded in prices. If, for example, market quality is higher for the Euro than for the Canadian dollar, the price of the Euro is expected to impound common information more rapidly than does the Canadian dollar. In this event, we would expect to see innovations in returns and/or volatility for the Euro having predictive content for the less actively traded Canadian dollar.

We examine return and volatility spillovers between the Canadian dollar and the Euro over the trading day by estimating a GARCH model similar to Baillie and Bollerslev (1990) and Engle, Ito and Lin (1990). Our model extends these studies in three ways: (a) we use finer intervals (15 minute, rather than the more commonly used hourly, intervals); (b) we investigate differences in information incorporation and spillovers across geographic regions; and (c) we examine changes in information flow associated with market openings and closings which are believed to be associated with large flows of new information (e.g., Bloomfield, O'Hara and Saar (2005)).

The model includes dummy variables and interaction effects to explicitly capture differences (i) in trading and quoting behavior across geographic markets, and (ii) during the first (opening) and last (closing) hour of trading in each market. These variables allow us to determine whether there are differences in information spillovers in different geographic segments and at times of concentrated information arrival (such as the opening and closing of markets, when informed traders are believed to be most active). Formally, our model is defined as:

$$r_{A,t} = \alpha_{A,t} + \rho_{A,0} r_{A,t-1} + \rho_{B,0} r_{B,t-1} +$$

$$\sum_{i=1}^{4} \rho_{A,i} Dgeog_{i,t} r_{A,t-1} + \sum_{i=1}^{4} \rho_{B,i} Dgeog_{i,t} r_{B,t-1} +$$

$$\sum_{i=5}^{6} \rho_{A,i,open} Dopen_{i,t} r_{A,t-1} + \sum_{i=5}^{6} \rho_{B,i,open} Dopen_{i,t} r_{B,t-1} + \qquad (3a)$$

$$\sum_{i=7}^{8} \rho_{A,i,close} Dclose_{i,t} r_{A,t-1} + \sum_{i=7}^{8} \rho_{B,i,close} Dclose_{i,t} r_{B,t-1} + \varepsilon_{A,t}$$

where $\varepsilon_{A,t} \sim N(0, h_{A,t})$ and

$$h_{A,t} = a_{A,0} + a_{A,1} \varepsilon_{A,t-1}^2 + a_{A,2} h_{A,t-1} + a_{B,1} \varepsilon_{B,t-1}^2 +$$

$$\sum_{i=1}^{4} c_i Dgeog_{i,t} + \sum_{i=5}^{6} c_i Dopen_{i,t} + \sum_{i=7}^{8} c_i Dclose_{i,t} +$$

$$\sum_{i=1}^{4} c_{A,i} Dgeog_{i,t} \varepsilon_{A,t-1}^2 + \sum_{i=1}^{4} c_{B,i} Dgeog_{i,t} \varepsilon_{B,t-1}^2 + \qquad (3b)$$

$$\sum_{i=5}^{6} c_{A,i,open} Dopen_{i,t} \varepsilon_{A,t-1}^2 + \sum_{i=5}^{6} c_{B,i,open} Dopen_{i,t} \varepsilon_{B,t-1}^2 +$$

$$\sum_{i=7}^{8} c_{A,i,close} Dclose_{i,t} \varepsilon_{A,t-1}^2 + \sum_{i=7}^{8} c_{B,i,close} Dclose_{i,t} \varepsilon_{B,t-1}^2$$

where A and B are the currency pairs; $r_{A,t}$ and $r_{B,t}$ are 15-minute returns for the two currencies; $Dgeog_{i,t}$ are regional dummies set to one for a particular region and zero otherwise (i is 1 for Asia, 2 for Europe, 3 for the overlap in European/North American trading and 4 for North American trading, with the base case being post-North American trading); $Dopen_{i,t}$ and $Dclose_{i,t}$ are dummies for the hour corresponding to the opening and closing of the two major markets (for the openings, i is 5 for Europe and 6 for North America; for the closings, i is 7 for Europe and 8 for North America); $h_{A,t}$ and $h_{B,t}$ are conditional volatilities; and $\varepsilon_{A,t-1}^2$ and $\varepsilon_{B,t-1}^2$ are lagged volatility innovations.[12]

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[12] We use numeric subscripts in (3a) and (3b) for the sake of brevity. To ease interpretation, we use actual descriptors for currency and market in the text and tables. We have also estimated specifications that allow for different geographic means in (3a) as well as Asian market opening and closing/announcement effects in (3a) and (3b). The coefficients on these variables are close to zero and not statistically significant, so we exclude them in the interests of parsimony.

Before turning to the results, we discuss estimation of the lagged volatility innovation for the 'other' currency pair. In principle, it would be best to use the innovation from a multivariate GARCH model, which jointly estimates the volatility dynamics for the currencies (see Bollerslev, Engle and Wooldridge (1988) and Baba, Engle, Kraft and Kroner (1991)). However, multivariate GARCH models cannot easily accommodate the number of parameters in our examination of geographical variations in spillovers. Hence, we follow Baillie and Bollerslev (1990) and Hamao, Masulis and Ng (1991) in adding the squared innovation from a univariate GARCH model for the Canadian dollar to a (univariate) GARCH model for the Euro, and vice versa.[13]

The results are presented in Table 2 and Table 3. We start with the Euro. In the conditional mean equation (results in Panel A), the estimated coefficient on lagged Euro returns ($\rho_{Euro,0}$) of -0.098 is significantly negative.[14] Note that this base case coefficient corresponds to post-North American trading. Intraday variations in the autocorrelation of Euro returns are given by the sum of the base case coefficient and the relevant regional coefficients. For instance, the autocorrelation in Euro returns is given by $\rho_{Euro,0} + \rho_{Euro,NA}$ during North American trading, and by $\rho_{Euro,0} + \rho_{Euro,EUR} + \rho_{Euro,EUR,Open}$ around the opening of the European markets. Table 3A presents the aggregate coefficients by region as well as the results of t-tests of whether these coefficients are significantly different from zero. The autocorrelation in Euro returns is negative during North American trading (the sum of the relevant coefficients is -0.083), even more negative during Asian trading (-0.12), slightly closer to zero during the overlap in European and North American trading (-0.067) and statistically indistinguishable from zero during European trading (-0.028, but with a t-statistic of -1.4). While the autocorrelation is insignificantly different from zero around the

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[13] Reassuring evidence is provided by Conrad, Gultekin and Kaul (1991), who estimate a univariate GARCH model (similar to the model we employ) and a multivariate GARCH model for large and small stock returns and find that these yield similar conclusions regarding volatility spillover dynamics.

[14] We use the term autocorrelation for the sake of brevity, though the coefficient is not strictly an autocorrelation. Unless stated otherwise, the effects described are statistically significant. As in Baillie and Bollerslev (1990), we estimate robust quasi-maximum likelihood standard errors. The traditional outer product standard errors are smaller, often only one-tenth as large.

opening and closing of the European markets, it is significantly below zero at the open and especially the close of the North American markets (coefficients of -0.09 and -0.18). Consistent with the variance ratio results, these results suggest that information is incorporated into prices most efficiently throughout European trading.

Next, we consider the effect of lagged Canadian dollar returns on Euro returns. Lagged Canadian dollar returns have little predictive power for Euro returns, except during North American trading (the coefficient is 0.06 and marginally significant). The latter fact suggests that information may be impounded in Canadian dollar prices before Euro prices during North American trading, and reinforces the variance ratio results showing that Canadian dollar market quality is highest during North American trading.

Turning to the conditional variance specification for the Euro (results in Panel B of Tables 2 and 3), the sum of the GARCH coefficients a_1 and a_2 indicate that volatility for the Euro is strongly persistent. The geographic coefficients on the lagged innovations in volatility for the Euro (shown as $c_{Euro,Region}$) indicate significant variations in the persistence of volatility. We expect volatility to display greater persistence when more information arrives or when the market is digesting news. Interestingly, we find that the magnitude of the effect of past volatility innovations in the Euro is largest during Asian trading (Table 3B shows that $a_{1,EUR} + c_{Euro,Region}$ is 0.106, 0.096, 0.084 and 0.083 for Asian, European-only, joint European-North American and North American–only trading). The stronger persistence of volatility during Asian trading could be the result of thinner trading which results in information shocks having a longer-lived effect on volatility. There is also increased persistence in volatility at the opening of European markets, plausibly due to a surge in the rate of information arrival.

Finally, we consider whether the Canadian dollar impounds information more quickly than the Euro by studying the coefficients on lagged Canadian dollar volatility innovations. The base

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case effect ($a_{1,CAD}$) is not statistically significant, but innovations in Canadian dollar volatility have predictive power during joint European-North American trading and especially at the opening of the North American market ($c_{CAD,EurNA}$, and $c_{CAD,NA,open}$ are at least weakly statistically significant). This predictive power of volatility innovations for the Canadian dollar is, once again, consistent with the variance ratio results showing high Canadian dollar market quality during North American trading[15].

Moving to the model estimated for the Canadian dollar, the conditional mean equation in Panel A of Table 2 reveals significant return reversals, with the base case coefficient on lagged returns being more negative than for the Euro (-0.13). Tests on the sums of the coefficients, summarized in Table 3B, show that the autocorrelation coefficient is indistinguishable from zero during the overlap in European and North American trading and significantly less negative than the base case coefficient during European-only and North American-only trading. As with our earlier variance ratio results, these indicate that market quality for the Canadian dollar increases during European trading, is highest during North American trading and lowest during Asian and post-North American trading. Similarly, the coefficients measuring the return autocorrelation around the opening and closing of markets are not significantly different from zero, except around the opening of the European markets (when the Canadian dollar is still very thinly traded).

In general, lagged Euro returns do not have predictive power for Canadian dollar returns. It is only during Asian trading that the estimated coefficient is significantly above zero, indicating that Euro returns predict Canadian dollar returns in this time zone. This is consistent with our variance ratio results for Asian trading (especially the latter half), showing that market quality for the dollar is low while that for the Euro does not deteriorate to the same extent.

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[15] Given the potential role for economic announcements in the observed changes around market openings, we also estimate a model including dummy variables for announcements in different markets. Specifically, we include levels and interaction dummy variables corresponding to the timing of major macro–economic announcements in the U.S. and Canada (8:30–9:30 a.m. EST) and the major European countries (France, Germany and Italy; 7:00–8:30 a.m. GMT). The coefficients on the dummies are insignificantly different from zero, and we do not present these results.

Comparing the sum of the GARCH coefficients for the Euro and Canadian dollar, we see that volatility is less persistent for the Canadian dollar than the Euro, perhaps due to less frequent information arrival. Table 3B shows that the effect of lagged Canadian dollar volatility innovations changes little in magnitude over the trading day. Also, despite the increased volatility around market openings and closings, we do not find increased persistence (over and above regional effects) in Canadian dollar volatility at these times.

Volatility innovations for the Euro predict volatility for the Canadian dollar during European-only and North American-only trading, and around the opening of both markets. The fact that common information is incorporated into the price of the Euro more rapidly is consistent with the variance ratio tests showing high market quality for the Euro around the opening of European markets. Recall that we also find evidence of a spillover from the dollar to the Euro at the opening of North American markets. At the opening of North American markets, therefore, there is weak evidence of bi-directional volatility spillovers. One explanation for this bi-directional spillover is the significant information flow at this time. Notably, U.S. macroeconomic announcements are likely to affect both the Euro-U.S. dollar and Canadian dollar–U.S. dollar exchange rates. The evidence of a spillover effect from the Euro to the Canadian dollar during European–only and North American–only trading when quoting activity is concentrated among active dealers is consistent with the conjecture that concentrated trading promotes market quality and the rapid incorporation of common information into prices.

In sum, the variations in market quality suggested by the intraday return and volatility dynamics for the two currency pairs are consistent with inferences drawn from the variance ratio tests. Specifically, we find evidence of return or volatility spillovers from the Canadian dollar to the Euro (Euro to the Canadian dollar) at times when the variance ratio tests show market quality for the Canadian dollar (Euro) to be high and/or quality for the other currency pair to be low. Strikingly, however, the return and volatility spillovers are not driven solely by differences in the

absolute level of trading activity. Were that the case, spillovers would always run from the much more heavily traded Euro to the Canadian dollar. Rather, our findings suggest that some common information is first incorporated into the price of the Canadian dollar at times when it is most actively traded and the variance ratio tests suggest its market quality is highest (during the overlap in European and North American trading). Similarly, the results indicate that increased geographic concentration of trading activity promotes the incorporation of information into prices.

4. Conclusions

The quality of asset markets captures the speed and accuracy with which price relevant information is impounded in prices. In this paper, we examine market quality for currencies, which has received relatively little attention. By considering two currency pairs that differ substantially in terms of trading activity, the Euro-U.S. dollar and the Canadian dollar-U.S. dollar, we can extend our understanding of the impact of variations in trading activity on market quality.

Our analysis uses a variance ratio measure of market quality, based on the ratio of the variances of longer-term and short-term returns. This measure shows that market quality for the Euro and Canadian dollar changes significantly over the trading day. The overall level of market quality is actually somewhat higher (though more variable) for the Canadian dollar than the Euro. Additionally, market quality for the Canadian dollar is highest when the dollar is most actively traded, but the same is not true for the Euro. We present evidence that the differences might be associated with differences in the number of dealers active in the two currencies as well as their geographic dispersion and with the dispersion in order flow.

As a broader, multivariate look at market quality, we estimate a GARCH model that captures return and volatility spillovers across the currencies. This analysis yields similar conclusions to those of the variance ratio analysis. We find that Euro returns and volatility predict Canadian dollar returns and volatility during periods when the variance ratio test shows high Euro

market quality and/or low Canadian dollar market quality. Likewise, Canadian dollar returns and volatility have predictive power for the Euro when the variance ratio test suggests high Canadian dollar market quality.

Overall, our use of foreign exchange data provides interesting insights into the influence of trading characteristics on asset market quality. Although it is believed that the level of trading activity is a key contributor to market quality, our study points to the importance of factors such as the numbers of active dealers and their geographic dispersion as well as the dispersion in order flow. The importance of such factors will only increase as markets become more global in scope.

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Figure 1: Trading hours in the foreign exchange market.

The figure shows the opening and closing hours (in Greenwich Mean Time, GMT) of the major financial centers for foreign exchange trading over the 24-hour trading day Because there are no clear opening and closing hours in the foreign exchange market, this figure indicates the approximate time at which traders in these markets become actively involved in foreign exchange trading.

| 00:00 | 04:00 | 08:00 | 12:00 | 16:00 | 20:00 | 24:00 |

Asia
opens

Europe
opens

North
America
opens

Europe
closes

North
America
closes

Asia
closes
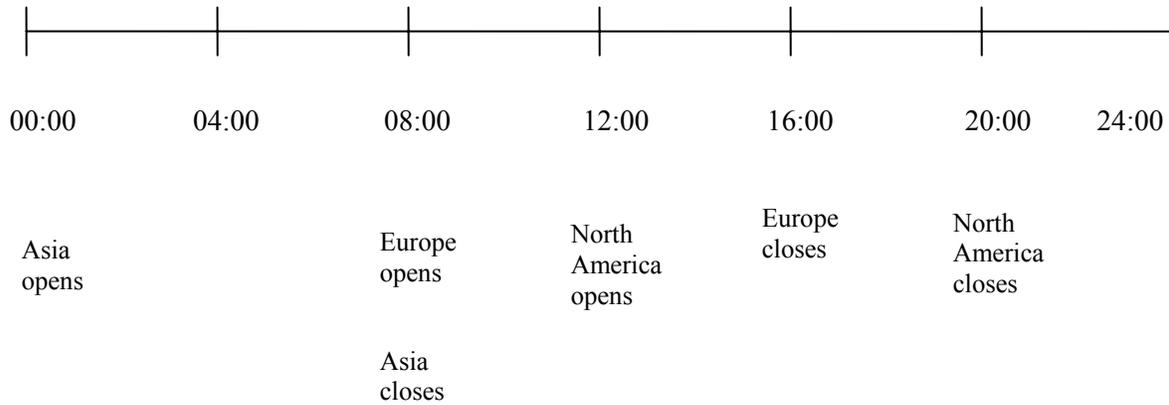
Figure 2: Intraday quoting frequency for the Euro-U.S. dollar and Canadian dollar-U.S. dollar.

The figure presents the average number of quotes in each 15-minute interval in the Euro-U.S. dollar and Canadian dollar-U.S. dollar spot market from January 1, 2000 through December 31, 2000.
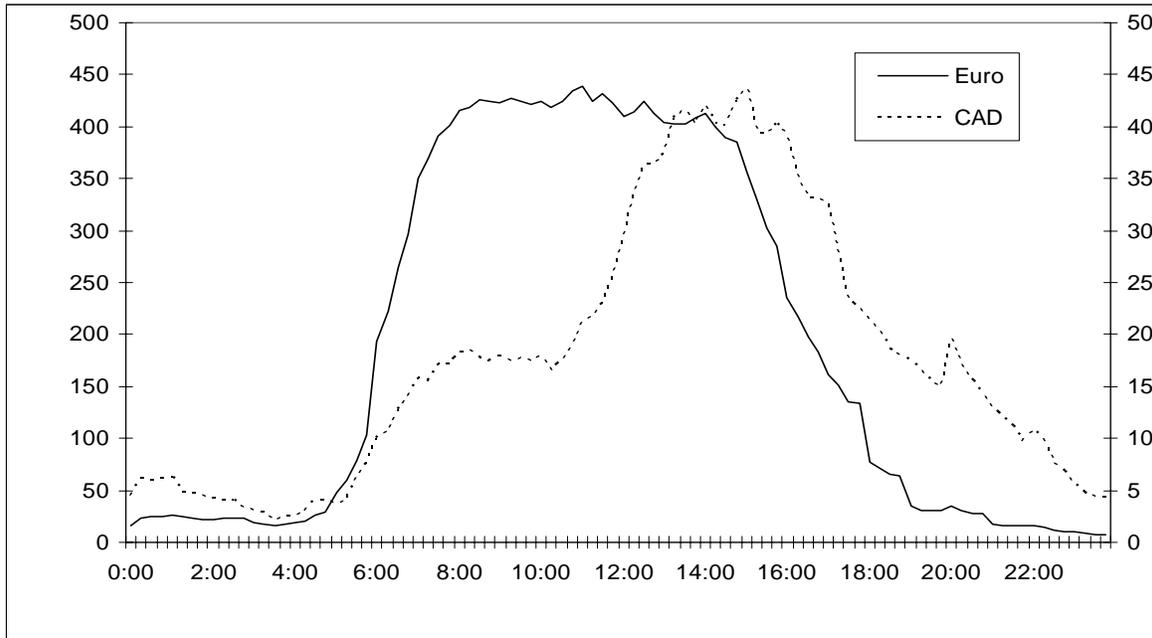
Figure 3: Intraday return volatility for the Euro-U.S. dollar and Canadian dollar-U.S. dollar.

The figure presents 15-minute return volatility in the Euro-U.S. dollar and Canadian dollar-U.S. dollar spot market from January 1, 2000 through December 31, 2000. Midpoint returns are computed using the last valid quotes in each 15-minute period, and the variance of the returns for each 15-minute interval is computed using the full year of returns for that period.
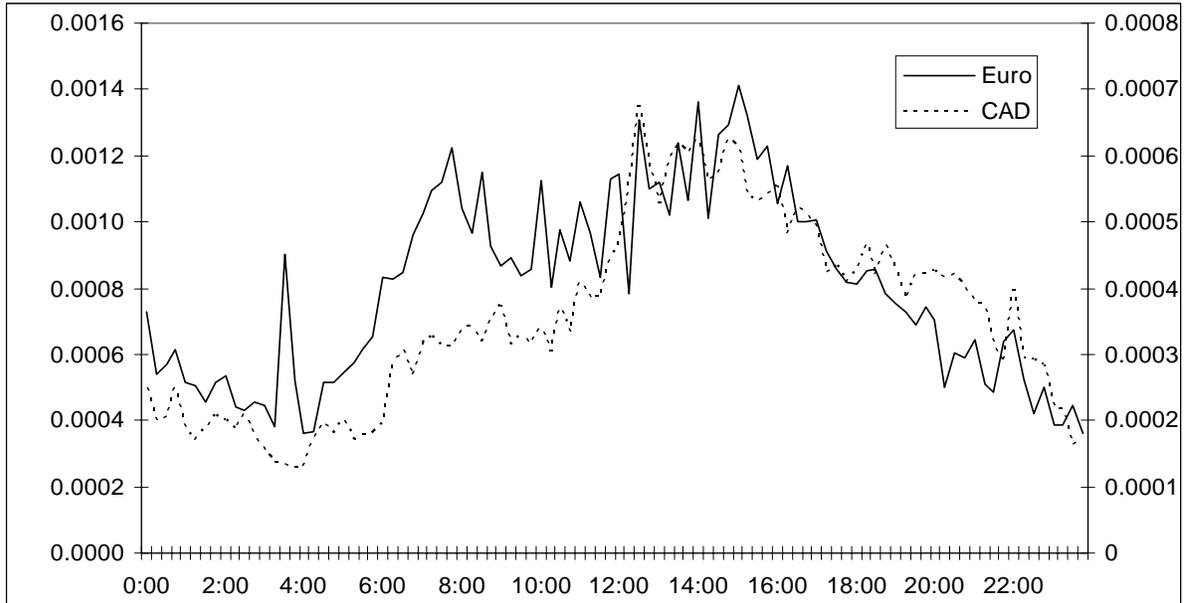
Figure 4: Concentration of Dealer Quoting Activity

The figure presents the average number of quotes submitted in each 60-minute interval divided by the average total number of quotes submitted over the day. The data for the Canadian dollar-U.S. dollar spot market are from January 1, 1995 through December 31, 1995 and for the Deutsche Mark- US dollar are from October 1, 1992 to September 30, 1993.

a) Percentage of Canadian dollar – US dollar Quotes Submitted by Dealers in Different Countries over the Trading Day

b) Percentage of Canadian dollar – US dollar Quotes Submitted by Active Dealers over the Trading Day

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c) Percentage of Deutsche Mark – US dollar Quotes Submitted by Dealers in Different Countries over the Trading Day

DM Nation of Origination of Overall Quotes

d) Percentage of Deutsche Mark – US dollar Quotes Submitted by Active Dealers over the Trading Day

DM Quoters by Overall Percent of Quotes Submitted

29
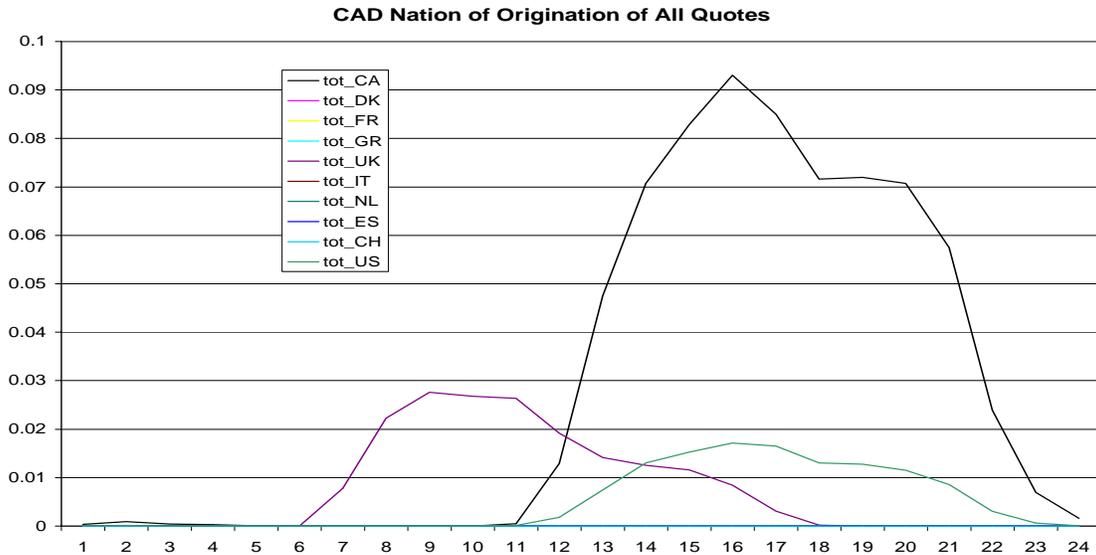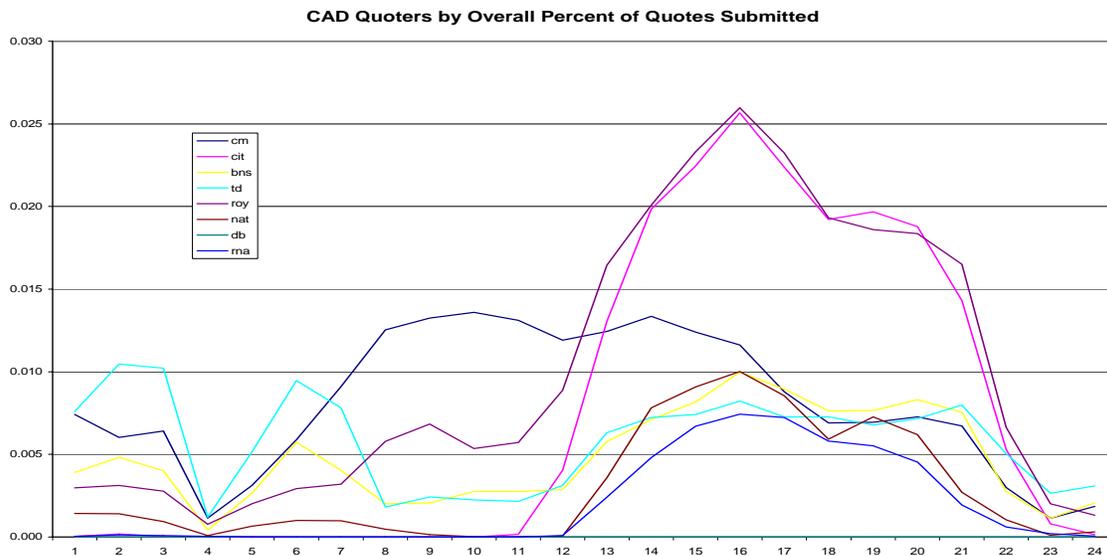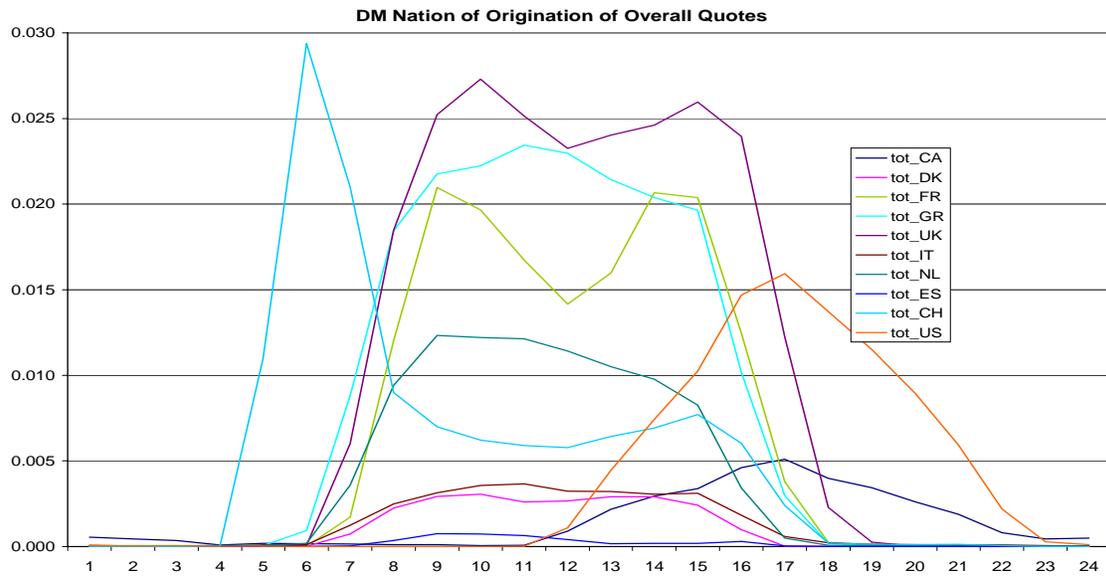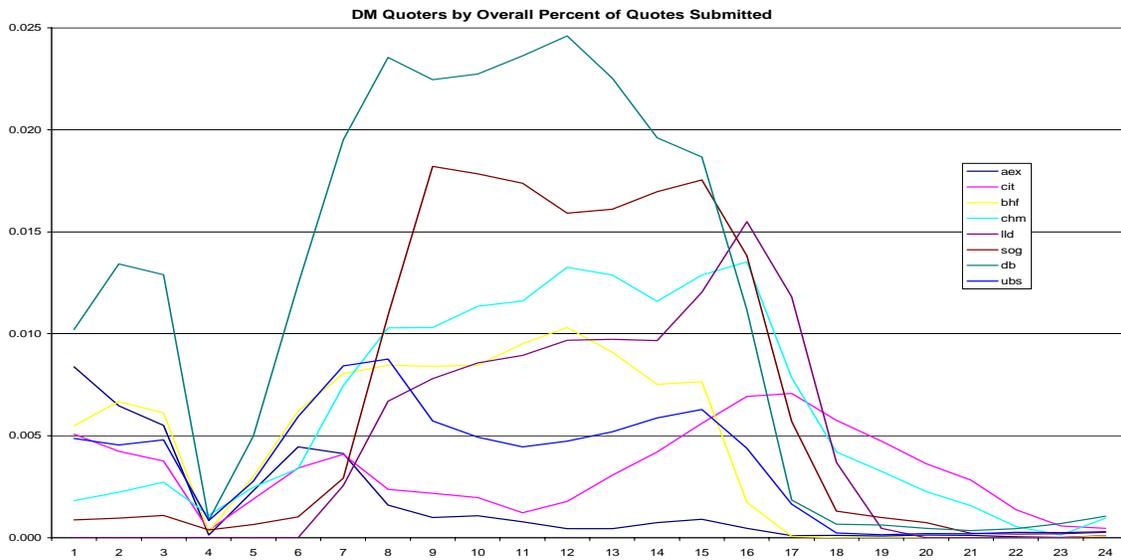
Table 1: Intraday Variance Ratios for the Euro-U.S. dollar and Canadian dollar-U.S. dollar.

Variance ratios are calculated for the Euro-U.S. dollar (Euro) and Canadian dollar-U.S. dollar (CAD) spot market returns. Two variance ratios are calculated: $VR_{semi-hourly} = Var(R_{30})/2Var(R_{15})$; and $VR_{hourly} = Var(R_{60})/4Var(R_{15})$. The z-statistics measuring the difference of the variance ratio from 1.0 are calculated as in Lo and MacKinlay (1988) and are distributed standard normal. The sample period is January 1, 2000 through December 31, 2000.

Hour ending	Euro, $VR_{semi-hourly}$		CAD, $VR_{semi-hourly}$		Euro, VR_{hourly}		CAD, VR_{hourly}	
	VR	Z-stat	VR	Z-stat	VR	Z-stat	VR	Z-stat
1:00	0.958	-0.89	0.921	-1.37	1.000	-0.01	0.892	-1.13
2:00	0.881	-2.85	1.002	0.05	0.803	-2.54	1.072	0.80
3:00	0.911	-1.75	0.959	-0.74	0.749	-2.70	0.935	-0.68
4:00	0.920	-0.75	0.914	-1.13	0.784	-1.20	0.677	-2.45
5:00	0.879	-2.05	0.782	-2.95	0.939	-0.49	0.745	-4.79
6:00	0.872	-2.99	0.843	-2.30	0.773	-2.75	0.722	-2.49
7:00	0.875	-2.69	0.790	-3.88	0.742	-3.00	0.796	-2.08
8:00	1.003	0.07	0.931	-1.51	1.026	0.35	0.850	-1.84
9:00	0.994	-0.14	0.931	-1.58	1.038	0.50	0.909	-1.14
10:00	0.966	-0.81	0.944	-1.31	0.955	-0.56	0.925	-1.00
11:00	0.979	-0.47	0.961	-0.89	1.081	0.98	1.037	0.44
12:00	0.967	-0.67	0.912	-1.98	1.011	0.12	0.932	-0.81
13:00	0.957	-0.89	0.982	-0.42	0.883	-1.34	1.045	0.59
14:00	0.855	-3.62	1.016	0.38	0.814	-2.44	0.991	-0.12
15:00	0.957	-1.19	1.010	0.26	0.901	-1.41	1.150	2.08
16:00	0.931	-1.80	0.991	-0.22	0.886	-1.64	0.933	-0.94
17:00	0.910	-2.28	1.030	0.68	0.824	-2.43	0.986	-0.17
18:00	0.971	-0.70	0.918	-1.92	0.884	-1.55	0.782	-2.86
19:00	0.869	-2.90	1.014	0.31	0.853	-1.81	1.063	0.72
20:00	0.814	-4.31	0.947	-1.20	0.685	-3.95	0.875	-1.50
21:00	0.914	-2.34	0.943	-1.42	0.863	-1.97	0.898	-1.43
22:00	0.925	-1.54	0.869	-2.92	0.932	-0.76	0.784	-2.69
23:00	0.953	-0.72	0.918	-1.56	0.849	-1.31	0.819	-2.09
23:59	0.905	-1.41	0.863	-2.53	0.759	-2.00	0.792	-2.35

Table 2: Information Spillovers in the Euro-U.S. dollar and Canadian dollar-U.S. dollar spot market.

Results for the GARCH model described by equations (3a) and (3b) for 15-minute returns in the Euro-U.S. dollar (Euro) and Canadian dollar-U.S. dollar (Canadian dollar) spot market. The sample period is January 1, 2000 through December 31, 2000. The variables are described in the text. The coefficient estimates and t-statistics for the Euro are in the first two columns, while those for the Canadian dollar are in the third and fourth columns. The estimated values for the coefficients are multiplied by 100. Coefficients on Euro and Canadian dollar returns and volatility are subscripted by Euro and CAD.

Panel A. Conditional mean.

Coefficient description	Coefficient	Euro		Canadian Dollar	
		Estimate	t-stat	Estimate	t-stat
Intercept	A	-1.04E-04	-0.29	1.50E-04	0.95
Base autoregressive coeff	$\rho_{Euro,\,0}$	-9.75	-4.98	-0.44	-0.44
Geog autoregressive coeff	$\rho_{Euro,\,Asia}$	-2.28	-0.91	1.58	1.46
Geog autoregressive coeff	$\rho_{Euro,\,Europe}$	6.96	2.50	1.04	0.85
Geog autoregressive coeff	$\rho_{Euro,\,EU/NA}$	3.01	1.09	1.15	0.83
Geog autoregressive coeff	$\rho_{Euro,\,NA}$	1.44	0.55	0.08	0.06
Base autoregressive coeff	$\rho_{CAD,\,0}$	2.25	0.69	-13.3	-5.88
Geog autoregressive coeff	$\rho_{CAD,\,Asia}$	2.04	0.43	1.99	0.70
Geog autoregressive coeff	$\rho_{CAD,\,Europe}$	-4.63	-0.86	6.98	2.25
Geog autoregressive coeff	$\rho_{CAD,\,EU/NA}$	-2.03	-0.42	13.3	4.42
Geog autoregressive coeff	$\rho_{CAD,\,NA}$	3.37	0.74	7.62	2.56
Eur open autoregressive coeff	$\rho_{CAD,\,Europe,\,open}$	8.01	0.95	-3.18	-0.96
Eur open autoregressive coeff	$\rho_{Euro,\,Europe,\,open}$	9.07	3.07	0.19	0.22
NA open autoregressive coeff	$\rho_{CAD,\,NA,\,open}$	-1.33	-0.16	0.042	0.01
NA open autoregressive coeff	$\rho_{Euro,\,NA,\,open}$	-2.53	-0.62	1.68	0.98
Eur close autoregressive coeff	$\rho_{CAD,\,Europe,\,close}$	11.90	1.49	-3.47	-0.92
Eur close autoregressive coeff	$\rho_{Euro,\,Europe,\,close}$	0.34	0.09	-0.18	-0.11
NA close autoregressive coeff	$\rho_{CAD,\,NA,\,close}$	-22.80	-3.50	3.67	0.83
NA close autoregressive coeff	$\rho_{Euro,\,NA,\,close}$	-10.12	-2.79	1.34	0.60

Panel B. Conditional variance.

Coefficient description	Coefficient	Euro		Canadian Dollar	
		Estimate	t-stat	Estimate	t-stat
Intercept	a_0	2.05E-06	1.56	2.00E-06	1.55
ARCH	$a_{1,\,EU}$	6.68	2.25		
ARCH	$a_{1,\,CAD}$			18.9	2.60
GARCH	$a_{2,\,EU}$	79.2	60.61		
GARCH	$a_{2,\,CAD}$			24.5	5.70
Geog dummies	c_{Asia}	3.11E-07	0.14	9.98E-07	0.36
Geog dummies	c_{Euro}	3.22E-06	1.34	3.81E-06	3.34
Geog dummies	$c_{EU/NA}$	1.00E-05	3.50	1.24E-05	10.06
Geog dummies	c_{NA}	4.40E-07	0.18	6.64E-06	5.63
Open/Close dummies	$c_{open,\,EU}$	1.40E-05	7.40	1.60E-06	0.79
Open/Close dummies	$c_{close,\,EU}$	4.35E-07	0.09	6.63E-07	0.30
Open/Close dummies	$c_{open,\,NA}$	1.19E-06	0.43	1.88E-06	1.38
Open/Close dummies	$c_{close,\,NA}$	9.98E-07	0.53	7.95E-07	0.37
Base volatility shock	$a_{1,\,Euro}$			0.022	0.04
Base volatility shock	$a_{1,\,CAD}$	3.04E-17	0.00		
Geog volatility shock	$c_{Euro,\,Asia}$	3.87	0.93	3.77E-21	0.00
Geog volatility shock	$c_{Euro,\,Europe}$	2.90	0.97	0.63	1.08
Geog volatility shock	$c_{Euro,\,EU/NA}$	1.70	0.55	0.84	1.32
Geog volatility shock	$c_{Euro,\,NA}$	1.61	0.51	0.94	1.40
Geog volatility shock	$c_{CAD,\,Asia}$	5.80	0.67	-3.48E-18	0.00
Geog volatility shock	$c_{CAD,\,Europe}$	1.10E-16	0.00	-1.03E-16	0.00
Geog volatility shock	$c_{CAD,\,EU/NA}$	17.3	2.31	-1.35E-16	0.00
Geog volatility shock	$c_{CAD,\,NA}$	3.89	0.61	3.54	0.46
Opening volatility shock	$c_{CAD,\,Europe,\,open}$	2.72	0.24	0.41	0.03
Opening volatility shock	$c_{Euro,\,Europe,\,open}$	2.29E-17	0.00	0.44	0.42
Closing volatility shock	$c_{CAD,\,Europe,\,close}$	0.55	0.05	-1.81E-16	0.00
Closing volatility shock	$c_{Euro,\,Europe,\,close}$	-1.51E-17	0.00	4.12E-20	0.00
Opening volatility shock	$c_{CAD,\,NA,\,open}$	19.1	1.69	5.29E-17	0.00
Opening volatility shock	$c_{Euro,\,NA,\,open}$	0.35	0.12	0.69	0.81
Closing volatility shock	$c_{CAD,\,NA,\,close}$	5.20	0.90	-1.75E-18	0.00
Closing volatility shock	$c_{Euro,\,NA,\,close}$	-2.98E-18	0.00	0.45	0.30

Table 3: Tests of Information Spillovers.

Using the coefficient estimates from the GARCH model described by equations (3a) and (3b), this table presents the overall effect (i.e. the aggregated coefficient) for geographic regions and market openings/closings, as well as the results of tests of the statistical significance of the overall effect. The results for the Euro are in the first two columns, while those for the Canadian dollar are in the third and fourth columns.

Panel A. Conditional mean.

Coefficient restriction	Euro Sum of Coefficients	t-stat	Canadian dollar Sum of Coefficients	t-stat
$\rho_{Euro,0} + \rho_{Euro,region}=0$				
$\rho_{Euro,0} + \rho_{Euro,Asia}$	-0.120	-7.69	0.011	2.59
$\rho_{Euro,0} + \rho_{Euro,Europe}$	-0.028	-1.40	0.006	0.84
$\rho_{Euro,0} + \rho_{Euro,EU/NA}$	-0.067	-3.47	0.007	0.74
$\rho_{Euro,0} + \rho_{Euro,NA}$	-0.083	-4.71	-0.004	-0.41
$\rho_{Euro,0} + \rho_{Euro,region} + \rho_{Euro,region,open/close}=0$				
$\rho_{Euro,0} + \rho_{Euro,eur} + \rho_{Euro,Europe,open}$	0.063	1.55	0.008	0.53
$\rho_{Euro,0} + \rho_{Euro,NA} + \rho_{Euro,NA,open}$	-0.093	-1.89	0.024	1.08
$\rho_{Euro,0} + \rho_{Euro,eur} + \rho_{Euro,Europe,close}$	-0.064	-1.51	0.005	0.28
$\rho_{Euro,0} + \rho_{Euro,NA} + \rho_{Euro,NA,close}$	-0.184	-4.04	0.010	0.40
$\rho_{CAD,0} + \rho_{CAD,region}=0$				
$\rho_{CAD,0} + \rho_{CAD,Asia}$	0.043	1.30	-0.114	-6.75
$\rho_{CAD,0} + \rho_{CAD,Europe}$	-0.024	-0.54	-0.064	-2.96
$\rho_{CAD,0} + \rho_{CAD,EU/NA}$	0.002	0.06	0.000	0.00
$\rho_{CAD,0} + \rho_{CAD,NA}$	0.056	1.78	-0.057	-2.93
$\rho_{CAD,0} + \rho_{CAD,region} + \rho_{CAD,region,open/close}=0$				
$\rho_{CAD,0} + \rho_{CAD,eur} + \rho_{CAD,Europe,open}$	0.056	0.56	-0.095	-2.09
$\rho_{CAD,0} + \rho_{CAD,NA} + \rho_{CAD,NA,open}$	-0.011	-0.12	0.000	0.01
$\rho_{CAD,0} + \rho_{CAD,eur} + \rho_{CAD,Europe,close}$	0.121	1.40	-0.035	-0.79
$\rho_{CAD,0} + \rho_{CAD,NA} + \rho_{CAD,NA,close}$	-0.171	-2.36	-0.021	-0.42

Panel B. Conditional variance.

Coefficient restriction	Euro		Canadian dollar	
	Sum of Coefficients	t-stat	Sum of Coefficients	t-stat
$a_{Euro, 1} + c_{Euro, region}=0$				
$a_{Euro, 1} + c_{Euro, Asia}$	0.106	5.61	0.000	0.02
$a_{Euro, 1} + c_{Euro, Europe}$	0.096	7.14	0.007	1.78
$a_{Euro, 1} + c_{Euro, EU/NA}$	0.084	6.62	0.009	2.04
$a_{Euro, 1} + c_{Euro, NA}$	0.083	7.77	0.010	2.05
$a_{Euro, 1} + c_{Euro, region} + c_{Euro, region,open/close}=0$				
$a_{Euro, 1} + c_{Euro, eur} + c_{Euro, Europe,open}$	0.096	2.29	0.005	0.36
$a_{Euro, 1} + c_{Euro, NA} + c_{Euro, NA,open}$	0.087	2.05	0.013	1.38
$a_{Euro, 1} + c_{Euro, eur} + c_{Euro, Europe,close}$	0.084	2.26	0.007	0.62
$a_{Euro, 1} + c_{Euro, NA} + c_{Euro, NA,close}$	0.083	2.07	0.014	0.91
$c_{Euro, region} + c_{Euro, region,open/close}=0$				
$c_{Euro, eur} + c_{Euro, Europe,open}$	0.029	0.92	0.011	1.16
$c_{Euro, eur} + c_{Euro, Europe,close}$	0.017	0.50	0.008	0.95
$c_{Euro, NA} + c_{Euro, NA,open}$	0.021	0.50	0.015	1.42
$c_{Euro, NA} + c_{Euro, NA,close}$	0.016	0.46	0.014	0.88
$a_{CAD, 1} + c_{CAD, region}=0$				
$a_{CAD, 1} + c_{CAD, Asia}$	0.058	1.13	0.189	1.54
$a_{CAD, 1} + c_{CAD, Europe}$	0.000	0.00	0.189	4.20
$a_{CAD, 1} + c_{CAD, EU/NA}$	0.173	3.28	0.189	7.62
$a_{CAD, 1} + c_{CAD, NA}$	0.039	1.25	0.224	8.14
$a_{CAD, 1} + c_{CAD, region} + c_{CAD, region,open/close}=0$				
$a_{CAD, 1} + c_{CAD, eur} + c_{CAD, Europe,open}$	0.027	0.20	0.189	1.19
$a_{CAD, 1} + c_{CAD, NA} + c_{CAD, NA,open}$	0.364	2.69	0.189	1.75
$a_{CAD, 1} + c_{CAD, eur} + c_{CAD, Europe,close}$	0.178	1.39	0.189	1.95
$a_{CAD, 1} + c_{CAD, NA} + c_{CAD, NA,close}$	0.091	1.15	0.224	2.05
$c_{CAD, region} + c_{CAD, region,open/close}=0$				
$c_{CAD, eur} + c_{CAD, Europe,open}$	0.027	0.22	0.004	0.04
$c_{CAD, eur} + c_{CAD, Europe,close}$	0.178	1.58	0.000	0.00
$c_{CAD, NA} + c_{CAD, NA,open}$	0.364	2.71	0.000	0.00
$c_{CAD, NA} + c_{CAD, NA,close}$	0.091	1.22	0.035	0.32