Exploitable Arbitrage Opportunities Exist in the Foreign Exchange Market

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Abstract

Exploitable triangular arbitrage opportunities exist in the foreign exchange market net of the bid-ask spread. Using binding bid-ask quotes at which trades could occur we show these opportunities exist over the entire twenty-four hour trading day. The size of these opportunities is time-varying, decreasing at times when more quotes are coming to the market and when bid-ask spreads are lower. Even at times of high market activity, the size of these opportunities appears sufficient to attract arbitrage trades. Our findings support the Grossman and Stiglitz view that arbitrage opportunities must exist to compensate arbitrageurs for engaging in this activity.

JEL classification: G14, G15
Keywords: Arbitrage; Foreign Exchange Market; Liquidity; Market Efficiency

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Exploitable Arbitrage Opportunities Exist in the Foreign Exchange Market

Abstract

Exploitable triangular arbitrage opportunities exist in the foreign exchange market net of the bid-ask spread. Using binding bid-ask quotes at which trades could occur we show these opportunities exist over the entire twenty-four hour trading day. The size of these opportunities is time-varying, decreasing at times when more quotes are coming to the market and when bid-ask spreads are lower. Even at times of high market activity, the size of these opportunities appears sufficient to attract arbitrage trades. Our findings support the Grossman and Stiglitz view that arbitrage opportunities must exist to compensate arbitrageurs for engaging in this activity.

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The law of one price states that market efficiency will ensure any particular security will have just one price, no matter where the security is traded or how it is created. The Grossman and Stiglitz (1976, 1980) paradox states that there needs to be an "equilibrium degree of disequilibrium" for agents to collect costly information on which to trade. Arbitrage is costly and arbitrageurs need to be compensated for engaging in this activity. If markets are efficient at all levels then no agent will have the incentive to collect this costly information. Jensen (1978) argues that market efficiency will move prices to the point where economic profits are zero. Economic profits are defined as risk adjusted returns net of all costs. Arbitrage profits may exist, gross of costs, but not net of costs. It has also been shown by Shleifer and Vishny (1997) that the textbook view of arbitrage, being the opportunity to profit at no risk and with no capital outlay, is a situation uncommon in capital markets as most arbitrage does entail some degree of risk and requires some capital outlay. Transactions need to be synchronized and ideally the profit should be immediately accessible following the transactions.

We study the nature and size of arbitrage opportunities in the foreign exchange market. In particular we examine trading solely on the EBS trading platform which accounts for approximately 50% of all spot foreign exchange transactions between banks and other financial institutions globally. Transactions executed on this trading platform were in excess of USD130 billion per day in 2005. We show that arbitrage opportunities do exist in this market and that the size of these opportunities is time-varying throughout the twenty-four hour trading day. The arbitrage opportunities we examine are triangular arbitrage opportunities on British Pounds, Swiss Francs and Japanese Yen against US Dollars and Euros. An example of a British Pound triangular arbitrage would be to sell US Dollars and buy British Pounds, sell Euros and buy US Dollars, and sell British Pounds and buy Euros.

There are a number of advantages in studying the nature and size of arbitrage opportunities within this environment. Most studies of arbitrage are very much affected by the risk and capital outlay issues raised by Shleifer and Vishny (1997). If the arbitrage opportunity is based around a security and its counterpart, synthetic or otherwise, there will be a fundamental risk attached to the arbitrage transaction if the two securities are not perfect substitutes. Also arbitrage opportunities normally occur across markets. For example a security such as a futures contract is sold in one market and bought in another. The profit from this type of arbitrage opportunity can only be realized if the opportunity is traded

away after the arbitrage transactions are complete. If this does not happen the arbitrageur may have to wait until the settlement of the contacts to collect the arbitrage profit. In fact Liu and Longstaff (2004) show that arbitrage portfolios typically experience losses initially. The risk of the opportunity remaining for some significant period of time can be due to noise trader risk or synchronization risk. Noise traders may keep prices apart on account of their trading activity (e.g. De Long, Shliefer, Summers and Waldmann (1990), or prices may not converge due to a lack of synchronization between markets, (e.g. Abreu and Brunnermeier (2002)).

Another point worthy of noting is the requirement of short-selling in many arbitrage strategies. Short sales constraints such as margin requirements and the ability to trade have been shown to be an impediment to arbitrage, (e.g. Lamont and Thaler (2003)). The arbitrage opportunities we examine do not involve fundamental risk, noise trader risk, synchronization risk, or margin costs, and short sales are not required.

Other problems that can arise with implementing arbitrage strategies include implementation costs, execution risk and the ability to transact. Implementation costs include the costs of finding the arbitrage opportunity and then implementing the strategy. These will clearly be more significant if the opportunity exists across different markets. The same applies to execution risk which is the risk of the arbitrage opportunity disappearing before all the trades required to take advantage of the opportunity have been completed. The trades required to take advantage of an arbitrage opportunity must be executed simultaneously to avoid any execution risk and this will be more difficult if the trades need to be executed in two or more different locations. While implementation costs and execution risk are not totally eliminated in the arbitrage opportunities we examine, they are certainly minimized.

Finally the ability to transact needs careful examination. Arbitrage opportunities in illiquid markets are always questionable as there is no guarantee that the required transactions can be completed without having an impact on price. In the foreign exchange market liquidity tends to be very high. This is particularly true of the EBS trading platform. Previous studies of the foreign exchange market have been hampered by the availability of data, however. The readily available Reuters data is based on indicative quotes only and where transaction data is available, this normally comes without volume. The EBS data used in

this study is binding quote data and any arbitrage opportunity found can be implemented with near certainty up to a maximum of one million units of the base currency. Given that the quote data is binding, we use this data to evaluate the arbitrage opportunities as we are able to determine their existence and magnitude independent of the bid-ask spread. Any arbitrage profits we find are therefore both obtainable in the marketplace and are actual profits to the arbitrageur. EBS transactions data is available for the period under study and is price-consistent with the bid-ask data. Our choice of setting to study arbitrage therefore has significant advantages over many other settings in which arbitrage opportunities have been examined.

The arbitrage opportunities we examine are present within two-minute time horizons[1] and can be exploited by executing three trades consecutively on an EBS trading screen. At the completion of the third trade the opportunity has been exploited and the profit secured. This profit is calculated net of the cost of spreads. The finding of positive but time varying arbitrage opportunities throughout the foreign exchange twenty-four hour trading day allows us to postulate as to the reasons why these opportunities exist. In the context of the Grossman and Stiglitz paradox, there is a positive payout to those traders engaged in arbitrage activity, even in a highly active financial market such as this. The payout is generally small, however, and may be viewed as no more than fair compensation for engaging in this activity. Also the arbitrage profits available in the marketplace increase as trading activity decreases throughout the trading day. This result supports the view that, as dealers and arbitrageurs can be interchangeable in our market setting, when there are more dealers in the market there will also be more arbitrageurs and competition between arbitrageurs will decrease their profits. It can also be argued that at times when fewer quotes are coming to the market and therefore liquidity levels are arguably lower, market makers will leave more money on the table for arbitrageurs to help in the process of expediting order balance. This is consistent with the Grossman and Miller (1988) view that there is a cost to immediacy.

Our results are of major economic significance given the size and importance of the electronic platforms for executing foreign exchange transactions. The 2004 BIS triennial survey of the foreign exchange market shows that average daily foreign exchange spot transactions amounted to approximately $US621 billion in that year. Of this approximately $US213 billion was attributed to transactions between banks and other financial

institutions. The EBS platform accounted for approximately 50% of these transactions at over $US100 billion daily in that year rising to $US130 billion daily in 2005 and $US145 billion daily in 2006. In 2006 the EBS platform had over 2000 foreign exchange traders operating from 800 floors in over 40 countries. Throughout this period e-trading systems have continued to increase their market share.

The rest of this paper is organized as follows. Section I gives a background overview of the foreign exchange market, a description of the data used in this study and the summary statistics. Section II discusses triangular arbitrage theory and application and the hypotheses of this paper. Section III gives the results and the conclusions are presented in Section IV.

I. Foreign Exchange Market: Background

A. Background

Daily global foreign exchange market turnover has risen steadily in recent times, more than trebling in terms of US dollar value over the last fifteen years. The only period that experienced a downturn was from 1998 to 2001, due mainly to the introduction of the Euro. The main components of daily foreign exchange turnover are the spot transactions, outright forwards and foreign exchange swaps. As reported by Galati and Melvin (2004), daily global spot transactions reported to the Bank of International Settlements (BIS) grew from $US317 billion in 1989 to $US621 billion in 2004. Outright forwards grew from $US27 billion to $US208 billion and foreign exchange swaps grew from $US190 billion to $US944 billion over the same period. Of the spot transactions in 2004, approximately $US213 billion was attributed to transactions between banks and other financial institutions. The EBS platform accounted for approximately 50% of these transactions at over $US100 billion daily. Since 2004 the market share of spot foreign exchange transactions taking place on electronic trading platforms has continued to increase and EBS has cemented its place as the market leader for these transactions.

While the foreign exchange market is seen as being highly efficient, empirical studies of this market have been somewhat hampered by the lack of data for analysis. The major source of foreign exchange data to date has been the Reuters indicative quote data. While

this data is useful in many ways it is indicative quote data only and the quotes are not binding. The availability of the EBS data with binding quotes up to a value of one million units of the base currency, US dollars and Euros for this study, allows for a more rigorous testing of the efficiency of this market.

B. The EBS Electronic Trading Platform

EBS is a provider of foreign exchange and precious metal trading technology which started operations in 1993. It was originally set up to provide a competitive alternative to Reuters inter-bank spot foreign exchange trading through a partnership agreement between twelve major international banks agreed to in 1990. Two more banks joined the partnership in 1993 and then in 1995 EBS acquired Minex Corporation, a consortium of Japanese banks, voice brokers and Telerate. EBS also acquired Citicorp Dealing Resources in 1996. By 2004 the shareholders of EBS comprised of thirteen major international banks. These were ABN AMBRO, Bank of America, Barclays, Citigroup, Commerzbank, Credit Suisse First Boston, HSBC, JP Morgan Chase, Lehman Brothers, S-E-Banken, The Minex Corporation, The Royal Bank of Scotland, and UBS. EBS is now the major marketplace for spot foreign exchange transactions with an average daily volume of USD145 billion in 2006. The EBS platform has over 2000 traders operating out of 800 floors in over 40 countries.

The major operators on the EBS system are the EBS partner banks, known as the Prime Banks. EBS also operates a system where smaller banks can trade as Prime Customers of the Prime Banks by utilizing the surplus credit of the Prime Banks. A daily credit limit is agreed between the EBS Prime Bank and the EBS Prime Customer which is monitored by EBS. An EBS Prime Customer can then trade on the same prices that the EBS Prime Bank has access to up to their daily credit limit.[2]

The cost of running an EBS trading terminal includes a fixed set-up cost, monthly charges and trade fees. The initial set-up cost and monthly charges will vary from country to country but for Australia, as an example, in 2006 the cost of the hardware and line installation was approximately AUD9,000 with monthly charges at approximately AUD4,620. For the EBS Prime Banks the trade fees are based on a three-tier system. For trades up to USD1 billion the fee is USD7.50 per million. For the next USD9 billion the fee is USD5.00 per million and USD3.50 per million after that. These trade fees are the

amount charged to the Prime Banks using the system and exclude any Prime Bank fee charged on to EBS Prime Customers. There are no settlement fees with EBS.[3]

C. Data Description and Summary Statistics

Our data are sourced from EBS for the 2005 calendar year. The foreign exchange market operates 24 hours a day. However, it experiences very thin trading from Friday 21:00 GMT until Sunday 21:00 GMT so we follow the established precedent in the literature (e.g. Anderson and Bollerslev (1998)) and remove this data. This adjustment is especially important when using EBS data as while the EBS system accepts quotes during this period, it is the time of the week when maintenance is carried out on the system so data may be less reliable during this period. In accordance with Anderson and Bollerslev (1998) we also remove data from 21:00 GMT the night before to 21:00 GMT on the evening of US holidays. The quotes, as shown on the EBS trading platform, must be good for a trade of up to one million units of the base currency when placed on the trading system.

Our original data contain quotes entered into the EBS system for 21 currency pairs.[4] Many currencies are only quoted versus the USD or EUR not both, which makes it impossible to determine if a triangular arbitrage opportunity exists. Three currencies are quoted against the USD and the EUR. These are the CHF, GBP, and JPY. Our data is very liquid. The most liquid currency pair is the USD/EUR with 2,757,130 quotes while the least liquid is the EUR/CHF with 1,202,815 quotes. We have 304 days of data and 7296 hours of data in our sample. On average we have 9,700 EUR/USD quotes per day and 378 EUR/USD quotes per hour. The corresponding numbers for the least liquid EUR/CHF pair are 3,957 quotes per day and 165 quotes per hour.

II. Arbitrage Theory and Application

A. General Arbitrage and Liquidity

Text book arbitrage is the ability to achieve a riskless profit with no capital outlay and no risk. Arbitrage opportunities may exist across different markets and/or across assets that can be designed to be perfect substitutes. The problems that arise in the market place are

generally of an inter-temporal nature or of a matching nature. There can be execution problems in transacting the required trades, particularly if these trades need to be executed across different markets. There can be noise-trader issues or synchronization problems that delay completion of the arbitrage opportunity when mispricing persists as shown by Abreu and Brunnermeier (2002). Different markets may continue to price identical assets differently through time and unless there is a mechanism to settle between markets this opportunity cannot be taken advantage of, at least in the short-term, leading to holding costs that need to be accounted for. There will always be search costs and transaction costs when exploiting an arbitrage opportunity. Finally products that appear identical may still have some subtle differences such as expiry times for derivative products. Numerous arbitrage opportunities have been reported in the literature but their economic value is often questionable.

While there are numerous studies that have reported the existence of arbitrage opportunities, our focus is on arbitrage in the foreign exchange market. Rhee and Chang (1992) examine arbitrage opportunities in the spot and forward foreign exchange market and find minimal opportunities for covered interest arbitrage but significant one-way arbitrage opportunities (see Deardorff (1979)). The data they use in this study is the Reuters indicative quotes data, however, and this data carries the significant problem that actual transactions may not be possible at the quoted prices even though banks may be obliged to trade if called for reasons of reputation (see Martens and Kofman (1998)). The EBS data used in this study is not subject to this problem. Akram, Rime and Sarno (2005) also consider covered interest arbitrage and one-way arbitrage opportunities in the foreign exchange market using Reuters data. In this case the authors were able to obtain transactions data from Reuters. Their findings supported those of Rhee and Chang. They find economically significant arbitrage opportunities in both cases though these opportunities are short-lived. However, they too use indicative quote data for the interest rate products so there is still no certainty that the arbitrage opportunities found could be exploited.

Shleifer and Vishny (1997) develop a model that focuses on the limits of arbitrage. Building on the real-world condition that arbitrage requires capital and does carry some degree of risk, Shleifer and Vishny (1997) show that arbitrage can be ineffective in extreme cases and that the actions of arbitrageurs can fail to eliminate these arbitrage

opportunities. Baker and Savasoglu (2002) consider arbitrage with risk in the mergers and acquisitions market and find abnormal returns to arbitrageurs, though again their activity does not eliminate the arbitrage opportunity. Limits to arbitrage are also shown to exist between parent companies and their subsidiaries in the equity market, (Mitchell, Pulvino and Stafford (2002)), and in the mortgage-backed securities market, (Gabiax, Krishnamurthy and Vigneron (2006)).

The principals of arbitrage and liquidity are closely related. Arbitrage opportunities will induce arbitrage activity which in turn will improve liquidity in the market. If the arbitrage opportunities are truly riskless then this activity should remove the opportunity, at least up to the point of the cost of engaging in the activity. Given that an arbitrage opportunity is the result of mispricing, the literature on mispricing and liquidity is important to this research. The generally held opinion is that higher liquidity leads to less mispricing. Chordia, Roll and Subrahmanyam (2006) address this issue within a market efficiency framework. An efficient market is one where mispricing does not occur and returns approach a random walk. They find that return predictability is lower during periods of high liquidity for NYSE stocks during 1993-2002. Sadka and Scherbina (2007) further show that less liquid stocks on the NYSE tend to be more overpriced than stocks with higher levels of liquidity.

The market maker provides liquidity and offers a bid-ask spread to cover order processing costs (e.g. Demsetz (1968) and Tinic (1972)), inventory holding costs (e.g. Stoll (1978), Amihud and Mendelson (1980) and Ho and Stoll (1981)) and adverse information costs (e.g. Copeland and Galai (1983) and Easley and O'Hara (1987)). Grossman and Miller (1988) develop a model that links market maker activity with the demand for immediacy. Market makers supply immediacy to traders who wish to trade at T_0 rather than T_1. They bear the risk of holding unbalanced inventories until the arrival of final buyers or sellers to the market at time T_1. Traders who wish to trade at T_0 pay a price for this immediacy which will decrease as the number of market makers increases. They show that the number of market makers in a market, and therefore the level of liquidity in that market, will be determined by the level of demand for immediacy in the long-run.

In a highly liquid market such as the foreign exchange market, for arbitrageurs to have a role to play they must be compensated for their activity frequently enough to stay in the

game. Market makers themselves have an incentive to leave some money on the table for those playing the role of an arbitrageur as their activity can help balance the inventories of individual market makers more quickly. Also as Grossman and Miller (1988) note, the bid-ask spread only shows what the market makers' take is in total. It does not show the returns to individual market makers who will normally execute one side of a transaction only. The more market makers there are operating at any point in time, the more liquidity there will be to satisfy the demands of immediacy. Also more market makers will be operating at times when more final buyers and sellers coming to the market. These two facts combined will lead to a lesser requirement to leave money on the table for arbitrageurs.

B. Triangular Arbitrage

The arbitrage we consider in this paper is triangular arbitrage, and as we have mentioned this type of arbitrage has the advantage of being much less risky to implement in practice than many other forms of arbitrage. There is no fundamental risk, noise trader risk or holding costs. Implementation costs are minimal given that the triangular arbitrage we consider is within the same market and for the same reason, synchronization risk is also minimized.

Triangular arbitrage is executed through the buying and selling of a currency through the quotes of two other currencies. As mentioned before, the arbitrage opportunities we examine are triangular arbitrage opportunities on British Pounds, Swiss Francs and Japanese Yen against US Dollars and Euros. Other studies have also found positive returns to triangular arbitrage strategies. Aiba, Hatano, Takayasu and Shimizu (2002, 2003) find opportunities exist for up to ninety minutes in each trading day between the yen-dollar, dollar-euro and yen-euro for the period January 25, 1999 to March 12, 1999. However, they use transactions data whereas the data we use in this study is binding quote data for which there can be more certainty as to the execution of trades.

C. Our Application

We identify arbitrage opportunities by generating three sample each containing quotes for the three currency pairs required to pursue triangular arbitrage. The first sample contains quotes for the USD/CHF, EUR/USD, and EUR/CHF, the second sample contains quotes

for the GBP/USD, EUR/USD, and EUR/GBP, and the third sample contains quotes for the USD/JPY, EUR/USD, and EUR/JPY. We sort the quotes in each sample by their time stamp. We then identify an arbitrage opportunities as follows:

1. Record the bid and ask prices of the first currency pair that is quoted.
2. Record the bid and ask prices of the second currency pair that is quoted.
3. Keep updating 1. and/or 2. with the most recent quote until the third currency pair is quoted.
4. Determine if an arbitrage opportunity exists. In the first instance we check this by selling currency 1 (e.g. USD/JPY) and buying currency 2 (e.g. EUR/JPY). Our net position after this trade is short USD / long EUR. We then compare the rate this EUR/USD purchase was made at to the rate quoted for currency 3 (e.g. EUR/USD). If the rate is lower we calculate the arbitrage profit by assuming we close the position out by selling at the currency 3 quote. If the rate is higher (implying a negative arbitrage profit) we recalculate the profit available by buying currency 1 and selling currency 2. This means we effectively sell the EUR/USD. This position is closed out with a purchase at the currency 3 quote. We assume all purchases are at the ask price and sales are at the bid price.
5. We require the third currency quote to occur within two minutes[5] of the first currency quote to minimize the chance that stale quotes are driving our results.

The following example is taken from the first day of our sample period, January 2, 2005, when the following quotes occurred.

[Insert Table I About Here]

We start by selling the EUR/CHF at the Bid of 1.5555. When then buy the EUR/USD at the ask of 1.3550. This gives us a long CHF / short USD exposure at 1.5555 / 1.3550 = 1.14797. We close this out by selling the CHF and buying the USD at 1.1420. These transactions will result in a profit as we sold the USD at 1.14797 and bought it at 1.1420. The profit in USD on this transaction is 0.5228%. Note that this profit is achieved net of

any bid-ask spread costs. That is this is compensation purely to the arbitrageur who rapidly moves to a balanced portfolio position at minimum risk.

We are deliberately conservative in the number of arbitrage opportunities we record. When there are three quotes within a two minute interval that are divergent enough to create arbitrage profits we record one arbitrage opportunity. A new quote is then posted for one of the currency pairs that would often also generate an arbitrage opportunity with the quotes for the other two currency pairs. Rather than record this as a second arbitrage opportunity, we disregard it as it would require the arbitrageur to initiate a second transaction with the dealer who posted the quote used in the original arbitrage opportunity. The convention within the EBS trading platform is that quotes have to be good for the 1 million units of the base currency so if this amount was already traded with the arbitrageur in the first transaction it is possible there would be nothing left to trade when the arbitrageur approached them a second time. To keep our analysis realistic we only record a second arbitrage opportunity when three sufficiently divergent quotes that have not previously been used in an arbitrage opportunity are posted.

D. Hypotheses

The foreign exchange market is a highly liquid market that trades on a 24-hour basis. While the level of trading activity will fluctuate throughout the trading day there will always be traders wanting to execute orders and the presence of arbitrageurs will help to expedite order execution. We therefore expect to find triangular arbitrage opportunities throughout the trading day based on the Grossman and Stigltz (1976, 1980) paradox, which states that there needs to be an "equilibrium degree of disequilibrium" for agents to collect costly information on which to trade.

H1: Triangular Arbitrage opportunities will exist throughout the trading day.

The twenty-four hour trading platform operated by EBS allows for trading to take place throughout the entire twenty-four hour day, however, the major centers see their major volume during their normal daylight hours of trading which are local time 9.00 to 17.00. The major currency dealing centers are London (with an approximate 50% share of the market), followed by New York, Tokyo, Zurich, and Frankfurt. The arbitrage opportunities

we examine are triangular arbitrage opportunities on British Pounds, Swiss Francs and Japanese Yen against US Dollars and Euros. We are therefore concerned with trading hours in the five centers above. In normal (winter) time London time equates to GMT so 9.00 to 17.00 London is 9.00 to 17.00 GMT. Tokyo 9.00 to 17.00 equates to GMT 0.00 to 8.00, and New York 9.00 to 17.00 equates to GMT 14.00 to 22.00.[6] These time zones relative to GMT can be depicted as follows:

[Insert Figure I About Here]

Ito and Hashimoto (2004) report that the UK and European centers account for about 50% of all world-wide currency trades while the Asian region accounts for approximately 20% and North American accounts for a little under 20%. We would therefore expect to see more quotes on the EBS trading platform during the hours of 9.00 to 17.00 in the UK. We therefore give our second hypothesis as follows:

H2: The number of quotes in each currency varies throughout the twenty-four hour trading day and is influenced by the normal trading hours of the major currency dealing centers.

In order for a triangular arbitrage opportunity to exist there must be three valid quotes in the market at any point in time. For this study we operate within a two-minute timeframe and all the arbitrage opportunities end on account of new quotes coming to the market. If arbitrage opportunities need to be present to keep arbitrageurs active in the marketplace it follows that the more quotes there are coming to the market the more arbitrage opportunities there will be. It should be noted that we do not consider the size of the arbitrage opportunity at this point merely whether an arbitrage opportunity exists. In a triangular arbitrage setting a high degree of precision in relative quotes is required to completely remove an arbitrage opportunity. Our third hypothesis is therefore the following.

H3: There is a positive relationship between the number of quotes and the number of arbitrage opportunities in any time period.

In line with the Grossman and Miller, (1988) model in which market makers supply immediacy to traders who wish to trade at T_0 rather than T_1, the price of this immediacy will decrease as the number of market makers increases. When more players are operating in the market place transacting at time T_0 will be more likely and therefore the cost for immediacy will be reduced. Therefore at times of high levels of activity the profits available to arbitrageurs will be less.

H4: There is a negative relationship between the size of arbitrage profits and the number of quotes coming to the market in any time period.

As more dealers come to the market, competition between the dealers increase and this reduces bid-ask spreads and profits, (Huang and Masulis (1999)). As dealers and arbitrageurs can be interchangeable in our market setting, when there are more dealers in the market there will also be more arbitrageurs and competition between arbitrageurs will also decrease their profits. Therefore at times of lower bid-ask spreads arbitrage profits will be lower and vice-versa.

H5: There is a positive relationship between arbitrage profits and bid-ask spreads.

III. Results and Discussion

In this section our results are presented and discussed. Our major findings are threefold. Arbitrage opportunities persist throughout the entire day after incorporating the impact of the bid-ask spread on arbitrageurs. We find that bid-ask spreads are larger when the market is less liquid, which is consistent with the findings of Huang and Masulis (1999) that there is an inverse relationship between the number of dealers in the market and the bid-ask spread. Finally, we find that arbitrage profits are larger when the market is less liquid, even after accounting for the fact that spreads are higher. This provides further evidence in support of the Grossman and Stiglitz Paradox (1976, 1980) which states that there needs to be an "equilibrium degree of disequilibrium" for agents to collect costly information on which to trade.

We present summary statistics for our arbitrage opportunities in Panel A of Table II. The number of arbitrage opportunities range from 774,502 for the EUR/USD, USD/CHF, and

EUR/CHF to 1,233,430 for the EUR/USD, USD/JPY, and EUR/JPY. This equates to an average of 2,547 and 4,057 per day respectively or 106 and 169 per hour respectively. We express the arbitrage profits in percentage terms with the USD as the base currency. The profit from each transaction is calculated on the assumption the currency purchases (sales) required to execute the arbitrage transaction are made ask (bid). This ensures the bid-ask spread is accounted for.

The profits range from just above 0% to just under 1%. There is positive skewness in the profits with the mean being higher than the median in each instance. Mean profits are just under 0.02% for arbitrage opportunities involving the CHF and JPY, but are considerably higher for those involving the GBP (0.0399%). The medians across the three sets of currency pairs range from 0.0189% to 0.0344%. As noted earlier, quotes have to be good for a minimum of one million units of the base currency. During the period we consider the USD was the weakest base currency so the minimum amount that could be applied to any arbitrage transaction is USD1m. This equates to median profits ranging from USD189 for the opportunities involving the CHF to USD344 for opportunities involving the JPY. These profits are clearly in excess of the trade fees incurred in executing the three trades required for the arbitrage transaction. EBS trade fees are a maximum of USD7.50 per million so total trade fees incurred would be no more than USD22.50

[Insert Table II About Here]

Our first hypothesis is that "arbitrage opportunities persist throughout the entire day." We investigate this by considering whether the mean and median arbitrage profits are statistically significantly different from zero. We apply the traditional t-test and the Wilcoxon test respectively. The results in Panel B of Table II indicate that there is strong support for this hypothesis. The mean and median profits generated for arbitrage within the three sets of currency pairs are statistically significantly different from zero at the 1% level.

We now consider how the level of quote activity varies throughout the 24 hour trading day. Ito and Hashimoto (2004) report that the UK and European centers account for about 50%

of all world-wide currency trades while the Asian region accounts for approximately 20% and North American accounts for a little under 20%. We would therefore expect to see more quotes on the EBS trading platform when the UK, European, and US centers are operating under normal business hours, followed be periods when just the UK and European centers are under normal business hours. We expect to see the start of the trading day (when Tokyo is the major center) and the end of the trading day (when the US is the major center) to experience the least activity.

In Figure II and Panel A of Table III we see that our results are broadly consistent with Hypothesis Two. The most quotes occur in periods two and three when there is the overlap in normal business hours between UK and Europe and the US and when the UK and Europe are the major centers. There is at least 40% less quotes per hour on average in period one when Tokyo is in normal business hours and Period 4 when the US is in normal business hours. The vast liquidity of the foreign exchange market is clearly evident. Even when the fewest quotes occur (for the EUR/USD, GBP/USD, and EUR/GBP in US trading) there is still an average of 166,011 quotes per hour, which equates to an average of just under 7,000 quotes per minute.

[Insert Table III About Here]

[Insert Figure II About Here]

We formally test Hypothesis Two using a dummy variable regression framework. Each regression specification includes a dummy variable which equals one if the period is the earlier period with the day and zero if it is the later period. GMM regressions are used with robust standard errors. The regression results, presented in Panel B indicate that the conclusions regarding differences in quote activity between different periods are indeed robust. Quote activity is statistically significantly lower when Tokyo is the major trading center when either the UK and Europe or the UK, Europe, and the US are operating in normal business hours. Similarly, there is statistically significantly less quote activity when the US is operating in normal business hours than when the UK and Europe or the UK, Europe and the US are operating normal business hours. Period 3, the period of

overlap between the UK and Europe and the US is the most liquid for the three currencies involving arbitrage with the CHF. However, period 2, which is when the UK and Europe are the major centers, is the period when there is the most liquidity for the three currencies involving arbitrage with the JPY and the three currencies involving arbitrage with the GBP.[7]

Our third hypothesis relates to relationship between the number of quotes coming to the market and the number of arbitrage opportunities created. We expect a positive relationship to prevail in our entire sample and in each sub-period. If arbitrage opportunities need to be present to keep arbitrageurs active in the marketplace it follows that the more quotes there are coming to the market the more arbitrage opportunities there will be. We test this hypothesis using the regression specified in Equation 1.

$$\textit{Number of Arbitrage Opportunities} = a_0 + a_1 \textit{Number of Quotes} + \epsilon. \quad (1)$$

We use the average number of arbitrage opportunities and quotes per hour in our regressions. GMM regressions are used with robust standard errors. The results presented in Table IV show there is strong support for our hypothesis. In the entire data and in each of the four sub-periods there is a statistically significant (at the 1% level) positive relationship between the number of quotes and the number of arbitrage opportunities.

[Insert Table IV About Here]

Based on the propositions of Grossman and Stiglitz (1976, 1980), we expect to see more profitable arbitrage opportunities created when there is less liquidity in the market. In other words, we expect to see more profitable arbitrage opportunities acting as an incentive for arbitrageurs to supply liquidity. Based on our earlier finding that there is more liquidity in the foreign exchange market between the hours of 10.00 and 17.00 GMT then in other periods we expect this to result in lower profit during this period than at the beginning and end of the trading day.

[Insert Figure III About Here]

The results displayed in Figure III lend support to our hypothesis. Mean profit for the triangular arbitrage opportunities involving the CHF, GBP, and JPY all display a U shape pattern. Profits start the trading day relatively high, then begin to fall around 06.00 GMT as the Tokyo session begins to draw to a close. Profits are lowest during the periods that the UK and Europe alone, and the UK, Europe and the US are in normal business hours, and then begin to increase around 17.00 GMT, which is when the UK and Europe are no longer in normal business hours.

We present the results we generate to formally test our hypothesis in Table V. We run the regression specified in equation 2. We use the average profit and the average number of quotes per hour in our regressions. GMM regressions are used with robust standard errors.

$$Arbitrage\ Profits = a_0 + a_1 Number\ of\ Quotes + \epsilon. \quad (2)$$

There is evidence of a negative relationship between the number of quotes entering the market and the average size of arbitrage profits in our entire data. Each of the a_1 coefficients in the "All" column of Table V is negative and statistically significant at the 1% level. We examine the robustness of this result by considering the relationship between profits and liquidity separately in each of the four sub-periods. The relationship is consistent in period 1, 3, and 4, but not in period 2. Rather, a positive relationship between profits and liquidity is evident in this period.

[Insert Table V About Here]

Our final hypothesis relates to the relationship between the size of arbitrage profits and the bid-ask spread. We expect there to be a positive relationship between the size of arbitrage

profits and the size of the bid-ask spread. We hypothesized earlier that there would be more profitable arbitrage opportunities on offer when there was less liquidity in the market and Huang and Masulis show spreads are higher when there is less liquidity; hence the positive relationship between profits and spreads.

We present the results we generate to formally test our hypothesis in Table VI. We run the regression specified in equation 2. We use the average profit and the average bid-ask spread per hour in our regressions. GMM regressions are used with robust standard errors.

$$Arbitrage\ Profits = a_0 + a_1 Spreads + \epsilon. \quad (3)$$

The results presented in Table VI indicate that the evidence is strongly in support of our hypothesis. There is a positive relationship between bid-ask spreads and arbitrage profits in our entire sample and in each of our sub-periods. This relationship is statistically significant at the 1% level in each instance. Taken together, our results imply that the incentive to provide liquidity is such that the larger arbitrage profits on offer are more than sufficient to offset the larger spreads that occur when the market is less liquid.

[Insert Table VI About Here]

IV. Conclusions

The law of one price states that market efficiency will ensure any particular security will have just one price, no matter where the security is traded or how it is created. The Grossman and Stiglitz (1976, 1980) paradox states that there needs to be an "equilibrium degree of disequilibrium" for agents to collect costly information on which to trade. Arbitrage is costly and arbitrageurs need to be compensated for engaging in this activity.

We study the nature and size of arbitrage opportunities in the foreign exchange market. In particular we examine trading solely on the EBS trading platform which accounts for

approximately 50% of all spot foreign exchange transactions between banks and other financial institutions globally. The arbitrage opportunities we examine are triangular arbitrage opportunities on British Pounds, Swiss Francs and Japanese Yen against US Dollars and Euros. An example of a British Pound triangular arbitrage would be to sell US Dollars and buy British Pounds, sell Euros and buy US Dollars, and sell British Pounds and buy Euros.

The arbitrage opportunities we examine are present within two-minute time horizons and can be exploited by executing three trades consecutively on an EBS trading screen. At the completion of the third trade the opportunity has been exploited and the profit secured. This profit is calculated net of the cost of spreads. We find evidence of positive but time varying arbitrage opportunities throughout the foreign exchange twenty-four hour trading day. This evidence of a positive payout to those traders engaged in arbitrage activity, even in a highly active financial market such as this supports the proposition of Grossman and Stiglitz (1976, 1980). The payout is generally small, however, and may be viewed as no more than fair compensation for engaging in this activity.

The arbitrage profits increase as trading activity decreases throughout the trading day. This result supports the view that, as dealers and arbitrageurs can be interchangeable in our market setting, when there are more dealers in the market there will also be more arbitrageurs and competition between arbitrageurs will decrease their profits. It can also be argued that at times when fewer quotes are coming to the market and therefore liquidity levels are arguably lower, market makers will leave more money on the table for arbitrageurs to help in the process of expediting order balance. This is consistent with the Grossman and Miller (1988) view that there is a cost to immediacy.

There are a number of advantages in studying the nature and size of arbitrage opportunities within this environment. The binding currency quotes are perfect substitutes so there is no fundamental risk. The termination point of the arbitrage transaction at which profit is realized occurs very quickly so there is minimal noise trader risk or synchronization risk.

There are few impediments to implementing arbitrage in this setting. There are no short-selling constraints and execution risk, which is the risk of the arbitrage opportunity disappearing before all the trades required to take advantage of the opportunity have been

completed, is also minimal. Finally, the nature of our data gives us confidence that any arbitrage profits we find are both obtainable in the marketplace and are actual profits to the arbitrageur. The EBS data used in this study is binding quote data and any arbitrage opportunity found can be implemented with near certainty up to a maximum of one million units of the base currency. EBS transactions data is available for the period under study and is price-consistent with the bid-ask data.

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Footnotes

1. We use two-minute intervals to minimize the possibility of stale quotes. However we obtain similar results if we use ten-minute intervals.
2. All the above information relating to EBS is sourced from the EBS website at www.ebs.com.
3. This data on EBS costings was supplied by EBS customer services.
4. We also have transaction data for each currency pair. The currencies are very liquid so transaction prices almost always occur at the previously quoted bid or ask prices or somewhere between the two. Although transaction data would therefore yield very similar results, we choose to use the binding quote data as these prices more accurately reflect the prices available to an arbitrageur to trade at.
5. We follow the approach of Akram, Rime, and Sarno (2006) and impose the two-minute restriction to ensure all quotes were "fresh".
6. In 2005 the United Kingdom had daylight saving from the 27th March to the 30th October and the United States had daylight saving from the 3rd April to the 30th October. For daylight saving (summer) time London 9.00 to 17.00 equates to GMT 8.00 to 16.00 and New York 9.00 to 17.00 equates to GMT 13.00 to 21.00. Japan does not have a daylight saving regime and at all times Zurich and Frankfurt are one hour ahead of the United Kingdom. We repeated our analysis for both daylight-saving and non-daylight saving periods and found our results to be consistent across the two periods.
7. Although there is variation in the level of profitability to arbitrage transaction in each of the time period we find that meaningful levels of profit can be earned in each time period. We repeat our Table II analysis separately for each different time period and find the smallest median profit in any time period is 0.0168% (for the USD EUR and CHF) compared to 0.0189% for the entire period.

Table I
Arbitrage Data Example
The data are sourced from EBS for the period January 1 2005 to December 31 2005. Triangular arbitrage opportunities are identified by comparing the three most recent quotes for each set of three currencies (providing no quote is older than two minutes). An arbitrage opportunity exists if there is a mismatch between these three currencies, after assuming an arbitrageur can buy (sell) at the quoted ask (bid) price. This table gives an example of quotes recorded on January 3 2005 that led to an arbitrage opportunity.

Time (GMT) HH:MM:SS	Currency Pair	Bid	Ask	Quote
21.14:15	EUR/CHF	1.5555	1.5566	1
21.14:37	EUR/USD	1.3541	1.3550	2
21.14:42	USD/CHF	1.1410	1.1420	3

Table II
Summary Statistics

The data are sourced from EBS for the period January 1 2005 to December 31 2005. Triangular arbitrage opportunities are identified by comparing the three most recent quotes for each set of three currencies (providing no quote is older than two minutes). An arbitrage opportunity exists if there is a mismatch between these three currencies, after assuming an arbitrageur can buy (sell) at the quoted ask (bid) price. Panel A contains summary statistics for profits, which are expressed as percentage return with the USD as the base currency. Panel B contains results for the statistics tests used to determine if the mean and medians are different to zero. The null hypothesis of no difference from zero is tested using the t-test and Wilcoxon test respectively.

Panel A: Summary Statistics

	N	Mean	Std	Min	LQ	Median	UQ	Max
USD_EUR_CHF	774,502	0.0227%	0.0261%	0.0000%	0.0111%	0.0189%	0.0276%	0.9955%
USD_EUR_GBP	1,034,472	0.0399%	0.0373%	0.0000%	0.0250%	0.0344%	0.0461%	0.9973%
USD_EUR_JPY	1,233,430	0.0217%	0.0171%	0.0000%	0.0114%	0.0197%	0.0281%	0.8129%

Panel B: Statistical Tests

	H_0: Mean = 0	H_0: Median = 0
USD_EUR_CHF	764.65***	1.500×10^{10}***
USD_EUR_GBP	1,087.13***	2.675×10^{10}***
USD_EUR_JPY	1,409.57***	3.803×10^{10}***

***statistically significant at the 1% level

Table III
Quote Activity in Different Time Periods

The data are sourced from EBS for the period January 1 2005 to December 31 2005. Triangular arbitrage opportunities are identified by comparing the three most recent quotes for each set of three currencies (providing no quote is older than two minutes). An arbitrage opportunity exists if there is a mismatch between these three currencies, after assuming an arbitrageur can buy (sell) at the quoted ask (bid) price. Panel A contains the average number of quotes per hour for each of the four major time zones. Period 1, which is 0.00 to 08.00 GMT, is when Tokyo is the major trading center. Period 2, which is 09.00 to 14.00 GMT, is when London is the major market operating normal business hours. During Period 3, which is 14.00 to 17.00 GMT, both London and New York are operating in normal business hours. New York is major market open in normal business hours in Period 4, which is 17.00 to 22.00 GMT. Panel B contains regression results relating to differences in the number of quotes between periods. Each regression specification includes a dummy variable which equals one if the period is the earlier period with the day and zero if it is the later period. GMM regressions are used with robust standard errors.

Panel A: Average Quotes Per Hour in Each Period

	1	2	3	4
USD_EUR_CHF	255,257	473,078	495,584	176,302
USD_EUR_GBP	244,986	568,360	556,458	166,011
USD_EUR_JPY	328,661	582,468	571,588	226,250

Panel B: Differences Between Periods

		1-2	1-3	1-4	2-3	2-4	3-4
USD_EUR_CHF	a_0	1877.29***	1966.60***	579.94***	1966.60***	579.94***	555.29***
	t-stat	90.03	77.44	33.13	67.29	26.94	20.24
	a_1	-1097.29***	-1186.74***	199.92***	-89.31***	1297.35***	1411.31***
	t-stat	-37.21	-33.04	7.69	-2.16	40.56	36.37
	R^2	0.7340	0.6850	0.0964	0.0092	0.7481	0.7249
USD_EUR_GBP	a_0	2255.40***	2208.16***	546.10***	2208.17***	546.09***	546.09***
	t-stat	81.89	71.94	25.34	64.54	51.65	19.63
	a_1	-1283.23***	-1236.00***	426.08***	47.23***	1709.31***	1662.08***
	t-stat	-32.95	-28.47	13.31	0.98	45.62	40.21
	R^2	0.6838	0.6176	0.2423	0.0019	0.7898	0.7448
USD_EUR_JPY	a_0	2311.38***	2268.21***	744.24***	2268.21***	744.25***	744.24***
	t-stat	95.45	80.60	35.16	70.54	29.66	26.58
	a_1	-1007.17***	-963.99***	559.97***	43.17***	1567.13***	1523.96***
	t-stat	-29.14	-24.22	17.81	0.95	42.04	36.64
	R^2	0.6328	0.5389	0.3640	0.0018	0.7613	0.0178

***statistically significant at the 1% level, **statistically significant at the 5% level

Table IV

Relationship between the Number of Quotes and the Number of Arbitrage Opportunities

The data are sourced from EBS for the period January 1 2005 to December 31 2005. Triangular arbitrage opportunities are identified by comparing the three most recent quotes for each set of three currencies (providing no quote is older than two minutes). An arbitrage opportunity exists if there is a mismatch between these three currencies, after assuming an arbitrageur can buy (sell) at the quoted ask (bid) price. Regression statistics are presented for the regression specification $Number\ of\ Arbitrage\ Opportunities = a_0 + a_1 Number\ of\ Quotes + \epsilon$. GMM regressions are used with robust standard err Period 1, which is 0.00 to 08.00 GMT, is when Tokyo is the major trading center. Period 2, which is 09.00 to 14.00 GMT, is when London is the major market operating normal business hours. During Period 3, which is 14.00 to 17.00 GMT, both London and New York are operating in normal business hours. New York is major market open in normal business hours in Period 4, which is 17.00 to 22.00 GMT.

		All	P1	P2	P3	P4
USD_EUR_CHF	a_0	-16.30***	-8.28***	-39.94***	-52.97***	-4.12***
	t-stat	40.08	-16.16	-29.35	-20.19	-7.69
	a_1	0.01***	0.12***	0.15***	0.15***	0.12***
	t-stat	433.60	222.54	183.30	122.25	195.05
	R^2	0.9688	0.6916	0.9570	0.9520	0.9680
	N	6048	2017	1512	756	1260
USD_EUR_GBP	a_0	-36.34***	-30.87***	-57.26***	-75.59***	-30.21***
	t-stat	-67.05	-35.37	-34.63	-25.64	-26.53
	a_1	0.17***	0.16***	0.17***	0.18***	0.16***
	t-stat	467.35	220.01	210.75	146.13	114.01
	R^2	0.9731	0.9601	0.9671	0.9659	0.9118
	N	6048	2017	1512	756	1260
USD_EUR_JPY	a_0	-37.67***	-24.92***	-78.65***	-81.09***	-20.05***
	t-stat	-73.36	-34.23	-53.91	-41.35	-30.39
	a_1	0.17***	0.15***	0.19***	0.19***	0.15***
	t-stat	536.17	301.90	258.85	230.24	247.00
	R^2	0.9749	0.9784	0.9780	0.9860	0.9797
	N	6048	2017	1512	756	1260

***statistically significant at the 1% level

Table V

Relationship between the Size of Arbitrage Profits and the Number of Quotes

The data are sourced from EBS for the period January 1 2005 to December 31 2005. Triangular arbitrage opportunities are identified by comparing the three most recent quotes for each set of three currencies (providing no quote is older than two minutes). An arbitrage opportunity exists if there is a mismatch between these three currencies, after assuming an arbitrageur can buy (sell) at the quoted ask (bid) price. Regression statistics are presented for the regression specification $Arbitrage\ Profits = a_0 + a_1 Number\ of\ Quotes + \epsilon$ .Profits are expressed as percentage return with the USD as the base currency. The average profit and number of quotes over one hour intervals are used in the regressions. GMM regressions are used with robust standard errors. The periods relate to four major time zones. Panel A contains the average number of quotes per hour for each of the four major time zones. Period 1, which is 0.00 to 08.00 GMT, is when Tokyo is the major trading center. Period 2, which is 09.00 to 14.00 GMT, is when London is the major market operating normal business hours. During Period 3, which is 14.00 to 17.00 GMT, both London and New York are operating in normal business hours. New York is major market open in normal business hours in Period 4, which is 17.00 to 22.00 GMT.

		All	P1	P2	P3	P4
USD_EUR_CHF	a_0	43.08***	42.44***	17.10***	20.95***	44.63***
	t-stat	98.18	67.28	89.19	60.29	35.28
	a_1	-0.12***	-0.10***	0.00***	-0.01***	-0.16***
	t-stat	-36.90	-15.49	2.31	-8.27	-10.77
	R^2	0.1840	0.1065	0.0035	0.0795	0.0848
	N	6040	2016	1512	755	1254
USD_EUR_GBP	a_0	62.49***	76.75***	32.14***	39.37***	51.96***
	t-stat	77.17	40.24	30.09	32.58	32.04
	a_1	-0.11***	-0.19***	0.02***	-0.02***	-0.06***
	t-stat	-22.14	-11.71	3.49	-3.76	-3.45
	R^2	0.0781	0.0655	0.0080	0.0184	0.0110
	N	6040	2016	1512	755	1254
USD_EUR_JPY	a_0	34.26***	25.90***	17.23***	20.77***	42.66***
	t-stat	107.13	75.92	62.41	48.21	48.60
	a_1	-0.07***	-0.02***	0.01***	-0.01***	-0.12***
	t-stat	-33.65	-9.30	5.64	-3.53	-14.10
	R^2	0.1578	0.0412	0.0206	0.0162	0.1367
	N	6040	2016	1512	755	1254

***statistically significant at the 1% level

Table VI

Relationship between Arbitrage Profits and the Size of Bid-Ask Spreads

The data are sourced from EBS for the period January 1 2005 to December 31 2005. Triangular arbitrage opportunities are identified by comparing the three most recent quotes for each set of three currencies (providing no quote is older than two minutes). An arbitrage opportunity exists if there is a mismatch between these three currencies, after assuming an arbitrageur can buy (sell) at the quoted ask (bid) price. Regression statistics are presented for the regression specification $Arbitrage\ Profits = a_0 + a_1 Spreads + \epsilon$. Profits are expressed as percentage return with the USD as the base currency. Spreads are calculated as (Ask – Bid) / ((Bid + Ask) / 2). The average profit and spread over one hour intervals are used in the regressions. GMM regressions are used with robust standard errors. The periods relate to four major time zones. Panel A contains the average number of quotes per hour for each of the four major time zones. Period 1, which is 0.00 to 08.00 GMT, is when Tokyo is the major trading center. Period 2, which is 09.00 to 14.00 GMT, is when London is the major market operating normal business hours. During Period 3, which is 14.00 to 17.00 GMT, both London and New York are operating in normal business hours. New York is major market open in normal business hours in Period 4, which is 17.00 to 22.00 GMT.

		All	P1	P2	P3	P4
USD_EUR_CHF	a_0	00.00***	00.00	00.00	00.00***	00.00***
	t-stat	-10.38	0.22	-0.3	-6.77	-7.06
	a_1	1.65***	1.41***	1.32***	1.57***	1.99***
	t-stat	88.99	45.17	35.82	43.91	32.54
	R^2	0.5674	0.5033	0.4594	0.7189	0.4581
	N	6040	2016	1512	755	1254
USD_EUR_GBP	a_0	0.00***	0.00***	0.00***	0.00***	0.00***
	t-stat	-15.71	-13.26	-10.36	0.82	2.6
	a_1	2.19***	2.47***	1.89***	1.49***	1.59***
	t-stat	76.73	50.08	52.62	23.42	18.44
	R^2	0.5067	0.5618	0.6471	0.4212	0.2399
	N	6040	2016	1512	755	1254
USD_EUR_JPY	a_0	0.00***	0.00**	0.00***	0.00**	0.00***
	t-stat	-24.59	-2.95	-4.01	-2.18	-10.49
	a_1	1.87***	1.43***	1.47***	1.44***	2.11***
	t-stat	105.34	56.97	39.17	30.11	39.44
	R^2	0.6474	0.6171	0.5040	0.5460	0.5532
	N	6040	2016	1512	755	1254

***statistically significant at the 1% level

Figure I
FX Trading Hours in the Main Centers
This figure displays the time of the day (in GMT) that each of the four major centers of FX trading are in normal business hours. Each center handles the majority of global trading during these times. We define four periods (P1 – P4) to help us test our hypotheses.

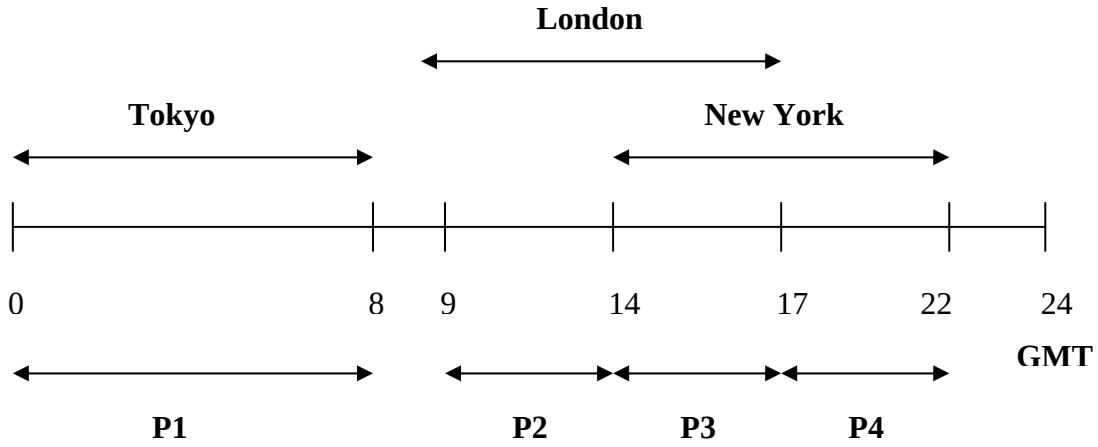

Figure II
Number of Quotes by Hour
The data are sourced from EBS for the period January 1 2005 to December 31 2005. Triangular arbitrage opportunities are identified by comparing the three most recent quotes for each set of three currencies (providing no quote is older than two minutes). An arbitrage opportunity exists if there is a mismatch between these three currencies, after assuming an arbitrageur can buy (sell) at the quoted ask (bid) price. The EUR and USD are common across each of the three arbitrage opportunities so CHF is the mean profit of CHF, USD, and EUR arbitrage opportunities, GBP is the mean profit of GBP, USD, and EUR arbitrage opportunities, and JPY is the mean profit of JPY, USD, and EUR arbitrage opportunities.

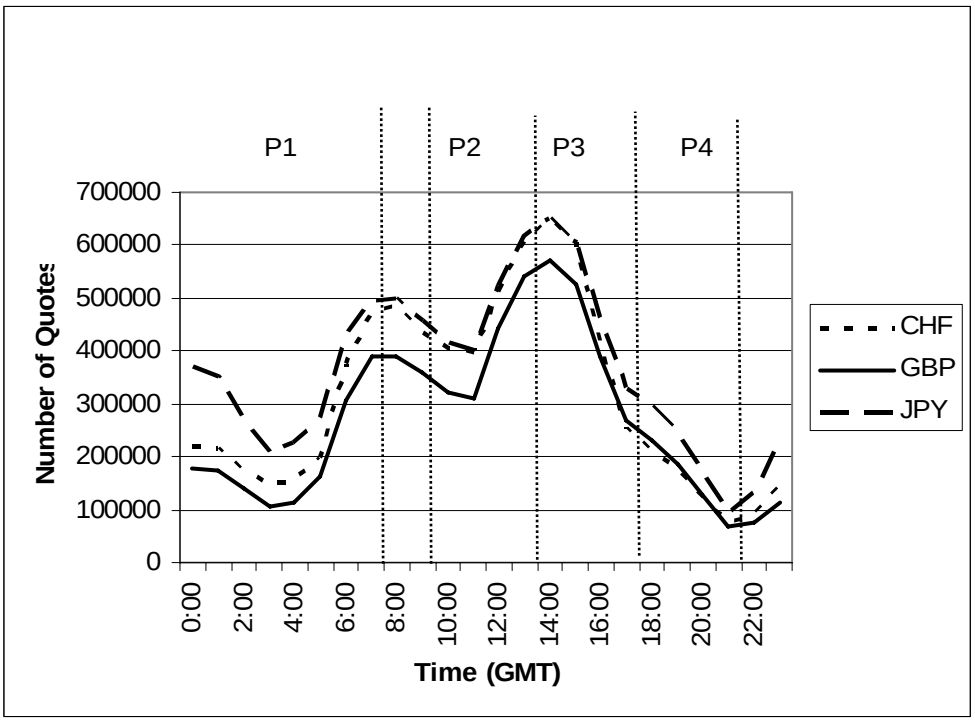

Figure III
Mean Profit by Hour

The data are sourced from EBS for the period January 1 2005 to December 31 2005. Triangular arbitrage opportunities are identified by comparing the three most recent quotes for each set of three currencies (providing no quote is older than two minutes). An arbitrage opportunity exists if there is a mismatch between these three currencies, after assuming an arbitrageur can buy (sell) at the quoted ask (bid) price. Profits are expressed as percentage return with the USD as the base currency. The EUR and USD are common across each of the three arbitrage opportunities so CHF is the mean profit of CHF, USD, and EUR arbitrage opportunities, GBP is the mean profit of GBP, USD, and EUR arbitrage opportunities, and JPY is the mean profit of JPY, USD, and EUR arbitrage opportunities.