Price Discovery for Competing Currency Numeraires

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For many countries, information in FX markets about the fundametals of their economies is reduced to two relevant and competing channels, namely, their currency's exchange rate with either the EUR or the USD. We present an analysis which can help to establish which one of these two currency numeraires drives the price discovery process and what market microstructure factors determine their informational contribution. Using data from Electronic Broking Services, we find that the USD is an informationally dominant currency for the Japanese economy but that such dominance is clearly contested when the two currencies are matched with the CHF. Although price discovery appears to positively correlate with the bid–ask spread, two-stage regressions present no evidence of a causal impact of liquidity. Furthermore, we provide evidence suggesting that managed exchange rates may affect the price discovery of their targets.

Keywords: Central bank intervention; Currency numeraire; Exchange rates; Liquidity; Price discovery; Target zones

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I. Introduction

This paper investigates price discovery in the world's biggest financial market using detailed quote and transaction data from Electronic Broking Services (EBS). Foreign exchange gravitates around two major currencies, the US dollar (USD) and the euro (EUR). Trading involving at least one of these two currencies exceeds 95 percent of the world's foreign exchange market turnover with the euro-dollar absorbing around a quarter of it (B.I.S., 2022). Hence, for most countries outside the eurozone and the US, news about the relative health of their economies will find an immediate reflection in their currency's exchange rate with the EUR or the USD.

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Previous papers on price discovery in FX markets study what drives price discovery in, for instance, EUR/USD or USD/JPY (see e.g. Bjønnes, Osler and Rime, 2020; Osler, Mende and Menkhoff, 2011; Covrig and Melvin, 2002; Cabrera, Wang and Yang, 2009). The goal in this study is to identify if the local currency's exchange rate with the USD or the EUR has the most dominant informational role, and to gain insights into what drives informed traders' choice of market. The paper also contributes in developing a framework for how to apply standard tools for identifying price discovery in a setting where the market prices (exchange rates) are not cointegrated.

Our analysis focuses on two currencies that have significant interdealer trading with both the EUR and the USD on EBS, namely the Swiss franc (CHF) and the Japanese yen (JPY). [1] We use data from the interdealer

1. EBS is the interdealer trading platform for major currencies except for Commonwealth currencies. A third major currency with significant trading with both the EUR and the USD, the British pound (GBP), has a majority of its interdealer trading on another interdealer trading platform, Refinitiv CME.

market because of its documented important role in the price discovery process (Bjønnes, Osler and Rime, 2020). The FX market is a two-tier market where dealers trade with customers on a bilateral basis, while their trading in the interdealer market reflects private information and residual inventories from trading with customers. In consequence, the interdealer market, and not the customer market, is the heart of the market and the locus of price discovery (Bjønnes, Osler and Rime, 2020; Bjønnes, Kathitziotis and Osler, 2022).[2]

Our approach applies standard tools for the evaluation of price discovery as a starting point, that is, information share (IS) (Hasbrouck, 1995), component share (CS) (Gonzalo and Granger, 1995; Harris, McInish and Wood, 2002), and their combined use into a refined measure called information leadership share (ILS) (Yan and Zivot, 2010; Putniņš, 2013). Frijns, Gilbert and Tourani-Rad (2015), Wang and Yang (2011), Hupperets and Menkveld (2002) and Hasbrouck (1995) use IS or CS in studying trading of an identical financial asset in two different venues. Other studies use the same tools focusing on trading via derivatives rather than their associated spot markets (e.g. Kryzanowski, Perrakis and Zhong, 2017; Chen and Gau, 2010; Mizrach and Neely, 2008; Chakravarty, Gulen and Mayhew, 2004; Cabrera, Wang and Yang, 2009). ILS has gained a great deal of prominence in recent years. Comerton-Forde and Putniņš (2015) examine the relative importance of dark and lit markets for a sample of stocks. Hauptfleisch, Putniņš and Lucey (2016) investigate price discovery in spot and future markets of gold, while Patel et al. (2020) focus on equity options versus their associated underlying stocks. There are also complementary approaches to IS, CS and ILS. A salient example is Muravyev, Pearson and Broussard (2013), who also study the potential informational role of equity options. However, the overwhelming majority of the studies involve at least one of the former three approaches.

In our analysis, we cannot use these standard tools directly because our focus is on two exchange rates that are not cointegrated, the price of the local currency in terms of the EUR or the USD. To get around this problem, we first obtain IS and CS for each competing exchange rate with its synthetic rate, in a similar fashion to De Jong, Mahieu and Schotman

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2. Cabrera, Wang and Yang (2009) examine the contribution to the price discovery of the EUR and the JPY against the USD in three foreign exchange markets based on electronic trading systems: CME GLOBEX regular futures, E-mini futures, and the EBS interdealer spot market. They find that the spot market (EBS) is consistently leading the price discovery process for both currencies.

(1998). For instance, for EUR/CHF we calculate the synthetic rate using USD/CHF and EUR/USD. Due to the asymmetric presence of noise [3] in this pair of two parallel processes (exchange rate and synthetic rate), we use IS and CS as input for the computation of ILS as suggested in Yan and Zivot (2010) and Putniņš (2013). Our empirical work confirms that the asymmetric presence of noise is a primary driver of IS, obfuscating the true information leadership component. By focusing exclusively on IS, our results will be largely reversed. According to Patel et al. (2020), there are two forms of bias in IS and CS caused by noise: (1) bias towards zero for the noisier market and (2) bias inwards from the zero/one endpoints. The analysis by Patel et al. (2020) shows that ILS corrects for the first form of bias. Patel et al. (2020) introduce an information leadership indicator (ILI) that builds directly on ILS, and corrects for both forms of bias. In a final step, we obtain the relative information leadership share (RILS) by computing the logarithmic ratio of ILS for the local currency's exchange rate with the EUR over ILS for the local currency's exchange rate with the USD. Since the ILS also depends on the movements in EUR/USD, the local currency's exchange rate with the EUR or the USD can both lead and lag the numeraire exchange rate (EUR/USD). RILS helps us to isolate the effect on the local currency, quantifying the dominance of the EUR rate with respect to its USD counterpart by excluding the common signal affecting both competing exchange rates.Similarly, we calculate the relative leadership indicator (RILI) and the relative information share (RIS). Our results suggest that the local currency's exchange rate with both the EUR and the USD can be important for price discovery, and that the importance of these markets is time-varying. Although turnover in USD/CHF is much higher than in EUR/CHF (B.I.S., 2022), we find that EUR/CHF may have the dominant informational role over long periods. For the JPY, USD/JPY has a dominant role for price discovery, while EUR/JPY has been important in some periods. To improve our understanding of the variation over time, we proceed by examining what drives traders' choice of market. The bid–ask spread turns out to be a significant explanatory variable of price discovery. The direction of this co-movement suggests that, in equilibrium, the tendency of market makers to fence off informed traders by widening spreads (Glosten and Milgrom, 1985) seems to prevail in contrast with the liquidity hypothesis (Fleming, Ostdiek and Whaley,

3. We will refer to temporary price changes that occur due to microstructure frictions (e.g. tick size discreteness or illiquidity) as noise.

1996). Furthermore, trading volume has significant explanatory power, whereas volatility does not seem to play a role. Our empirical work may also shed light on price discovery in managed exchange rate regimes. Specifically, we analyze price discovery around the implementation of the EUR/CHF peg by the Swiss National Bank on September 6, 2011. Our analysis suggests that the target of the controls (EUR/CHF) experiences an increase in informational leadership. We also consider a potential endogeneity issue with respect to liquidity. Informed traders may choose in which market to trade based on relative liquidity, and this choice may affect liquidity. To disentangle these effects, we run a two-stage regression using volatility as an instrument for the bid–ask spread. We find that liquidity has an insignificant causal effect on informed traders' choice of market. Patel et al. (2020) document a strikingly similar finding in the context of options and their underlying stocks. Building on this result, we address the connection between quote staleness and informational disadvantage in a final discussion.

We also discuss how our approach can be extended to the analysis of potential numeraire contenders. The rise of Asia, and in particular China, is likely to be conducive to a smaller and smaller influence of the EU and the US in the world economy. This reduced influence may distort the current ranking of currencies and thereby question the privileged status of the USD and the EUR. We believe our approach should also be useful in addressing other questions in future research. For instance, we could analyze price discovery around information events. Furthermore, we may analyze price discovery around FX fixes, and investigate how changes in fix benchmarks may alter the price discovery process. The analysis in this paper has some connections with previous work on currency competition dating back to Krugman (1980) and followed by Magee and Rao (1980) and Matsuyama, Kiyotaki and Matsui(1993), among others. Their goal is to examine the macroeconomic factors that turn currencies into vehicles through which transactions between other currencies take place. Instead, our focus lies on the informational value of the two currencies, which already display this currency numeraire role. We may also interpret our efforts as the analysis of exchange rate competition rather than currency competition. Indeed, departing from the numeraire status of the USD and the EUR, the latter depicts an informational rivalry being resolved on several fronts whereas the former delivers as many such rivalries as there are relevant smaller economies.

The paper is organized as follows. Here, section II introduces the methodology. The data and empirical strategy are described in Section

III. Sections IV and V contain the bulk of our empirical evidence. Our conclusions are confined to the last section.

II. Methodological preliminaries and data description

Although the exact meaning of price discovery has often been taken for granted rather than clearly stated, it seems to be the consensus that it aims at determining the relative speed at which different markets incorporate relevant information about the efficient price of the same asset or an asset and its replica[4]. Hasbrouck (1995) produces the first successful quantification of this important concept, the information share (IS), based on estimating the fraction of the variance of the shocks to the unobserved efficient price explained by the shocks to the observed prices in different markets. This formalization relies on a vector error correction model (VECM). Based on the work of Gonzalo and Granger (1995), Harris, McInish and Wood(2002) derive a closely related measure of price discovery, the component share (CS), which also use a VECM but which entirely rely on the speed of adjustment coefficients of each of the model equations.

Yan and Zivot (2010) and Putniņš (2013) prove that IS and CS are clearly biased in the presence of asymmetric levels of noise (microstructure frictions or illiquidity). IS and CS tend to assign larger price discovery to markets with lower levels of noise. These authors suggest a new measure, information leadership share (ILS), that builds on IS and CS, but removes the influence of noise.

The initial empirical contributions to the subject, including the seminal work of Hasbrouck (1995) and Harris, McInish and Wood (2002), focus on a framework where an identical asset is traded in different venues. However, it did not take long before researchers realized that the same approach could be applied to examining the price discovery of a given asset versus any associated derivative contract by exploiting the no-arbitrage relationship that connects both (see e.g. Booth, So and Tse, 1999; Chakravarty, Gulen and Mayhev, 2004). This paper also uses a similar connection, the one between an observed exchange rate and its associated implied (also known as synthetic) rate obtained via a triangular no-arbitrage condition. However, this relationship does

4. See Putniņš (2013) for an excellent discussion of this issue.

not directly deliver a price discovery evaluation of the two competing exchange rates, that is, the local currency's exchange rate with the EUR and the USD.

We now describe the details of our particular approach although we confine to the Appendix a full explanation of how IS and CS are actually computed.

A. *Synthetic quotes and relative information leadership shares*

For our purposes, the computation of the synthetic exchange rate will involve three currencies: the USD, the EUR, and a third one, which we will denote by C. Let A_{EC} denote the price of one EUR in units of currency C (in what follows referred to as the EUR rate), and let A_{DC} be the price of one USD again in units of currency C (the USD rate). A natural triangular relationship implicitly defines their associated synthetic rate I_{EC} and I_{DC}, and for example,

$$A_{EC} = A_{ED}A_{DC} \equiv I_{EC}$$

where the first equality must hold in the absence of arbitrage and the second one defines I_{EC}. The euro-dollar rate, A_{ED}, plays the role of the exchange rate numeraire in our analysis. Also, we can manipulate the above no-arbitrage equality to find the synthetic rate associated with A_{DC} as

$$A_{DC} = \frac{A_{EC}}{A_{ED}} \equiv I_{DC}$$

Acknowledging the realistic existence of a bid–ask spread requires defining instead synthetic bid and ask quotes, something that one can easily do by extending these definitions in a direct manner. The synthetic ask of the EUR rate will thus be given by $I^a_{EC} \equiv A^a_{ED}A^a_{DC}$

where A^a_{ED} and A^a_{DC} now denote actual ask quotes. The logic of this synthetic quote is sound since one can always obtain one EUR with units of currency C by buying first the exact amount of dollars with units of currency C that are required to purchase exactly one EUR. This amount happens to be $A^a_{ED}A^a_{DC}$. An identical argument justifies that the synthetic bid quote is defined as: $I^b_{EC} \equiv A^b_{ED}A^b_{DC}$. Similarly, the synthetic bid and ask quotes associated with the USD are obtained as:

$$I_{DC}^{a} \equiv \frac{A_{EC}^{a}}{A_{ED}^{a}} \qquad I_{DC}^{b} \equiv \frac{A_{EC}^{b}}{A_{ED}^{b}}. \tag{1}$$

No-arbitrage imposes that the following inequalities are satisfied,

$$I_{DC}^{a} > A_{DC}^{b} \qquad I_{DC}^{b} \quad < A_{DC}^{a}. \tag{2}$$

and identical constraints should hold for the corresponding EUR rates. Our approach will rely on midquotes and two parallel analyses for every currency C with two associated 2-dimensional processes given by

$$p_t^{EC} \equiv \left[\ln\left(\frac{A_{ECt}^{a}+A_{ECt}^{b}}{2}\right) \ln\left(\frac{I_{ECt}^{a}+I_{ECt}^{b}}{2}\right) \right]$$
$$p_t^{DC} \equiv \begin{bmatrix} \ln\left(\frac{A_{DCt}^{a}+A_{DCt}^{b}}{2}\right) \\ \ln\left(\frac{I_{DCt}^{a}+I_{DCt}^{b}}{2}\right) \end{bmatrix}.$$

The no-arbitrage restrictions in (2) seem to be enough to guarantee support for the assumption of cointegration that is necessary to legitimize the computation of the information shares. Proceeding as indicated in the Appendix, information shares of the actual midquotes, IS_1^{EC} and IS_1^{DC}, and their associated component shares, CS_1^{EC} and CS_1^{DC}, can be obtained. Their information leadership shares, ILS_1^{EC} and ILS_1^{DC}, are given by [5]

$$LS_1^{EC} \equiv \frac{\left|\frac{IS_1^{EC}(1-CS_1^{EC})}{(1-IS_1^{EC})CS_1^{EC}}\right|}{\left|\frac{IS_1^{EC}(1-CS_1^{EC})}{(1-IS_1^{EC})CS_1^{EC}}\right| + \left|\frac{CS_1^{EC}(1-IS_1^{EC})}{(1-CS_1^{EC})IS_1^{EC}}\right|}.$$

with an identical expression for ILS_1^{DC}, but using instead IS_1^{DC} and CS_1^{DC}.

The values of ILS_1^{EC} and ILS_1^{DC} alone are interesting because they establish to what extent news is immediately incorporated in

5. Given the granularity of our data, the covariance term σ_{12} will turn out to be relatively small and the upper and lower bounds of the information shares are very close, thereby making their averages a reliable estimate of the information shares.

the EUR (USD) rate or whether it shows up first in its synthetic expression. However, these measures may be misleading in quantifying the dominance of the EUR rate with respect to its USD counterpart, which is the goal of our analysis. Since both ILS_1^{EC} and ILS_1^{DC} also depend on the movements in EUR/USD, the local currency's exchange rate with the EUR or the USD can both lead or lag the numeraire exchange rate. To determine if the local currency's exchange rate with the EUR or the USD has the most dominant informational role, we obtain the relative information leadership share (RILS) by computing the following difference:

$$\log ILS_1^{EC} - \log ILS_1^{DC} \tag{3}$$

RILS helps us to isolate the effect on the local currency C, quantifying the dominance of the EUR rate with respect to its USD counterpart by excluding the common signal affecting both competing exchange rates. [6] Positive (negative) values of this measure will suggest that the EUR (USD) rate leads price discovery. As Patel et al. (2020) show, there may be additional gains in terms of reducing the biases of noise from focusing on a measure that takes value one if (3) is positive, and zero otherwise. This binary variable is the relative information leadership indicator (RILI).

Any claims of price discovery dominance of a given rate in our empirical analysis will thus be based on RILS and RILI given their demonstrated ability to isolate leadership in the impounding of information (Yan and Zivot, 2010; Putniņš, 2013; Patel et al, 2020; Dimpfl and Peter, 2021). In addition, reporting results for IS may also be interesting for two reasons. First, the reader may also be interested in capturing the ability of a given rate to avoid noise in comparison with its competing one. Second, as in Patel et al. (2020), there is value in establishing the disparity of results and biases that may arise by favoring the use of IS instead of ILS.[7] Hence, we will also complement our analysis with the relative information share (RIS) given by

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6. In particular, neither $\overline{IS}^{EC}$ and $\overline{IS}^{DC}$ nor CS_1^{EC} and CS_1^{DC} necessarily add up to one.

7. This additional layer may also include CS. Our empirical results in that case are quite similar and thus we choose not to report them.

$$\log IS_1^{EC} - \log IS_1^{DC}$$

B. Data description

We use data from Electronic Broking Services (EBS), the major interdealer electronic limit order book for trading in the most active currency pairs (excluding Commonwealth currencies). It contains second-by-second best bid and ask quotes and trades together with their associated volume from January 1, 2003 to December 31, 2007 for those rates for which EBS is the global benchmark, that is, EUR/USD, EUR/CHF, EUR/JPY, USD/CHF and USD/JPY. Our empirical results will also use another sample covering two intervals, from January 1, 2011 to April 30, 2011 and from January 1, 2012 to April 30, 2012, of identical data but with 100-millisecond granularity. To lean on intervals of sufficient trading activity, we exclude all data outside the 3 AM to 11 AM New York time interval.[8] We also remove Saturdays and Sundays and all major US holidays as in Chaboud et al. (2014).

For our analysis, data from the interdealer market are superior because of its important role for price discovery (Bjønnes, Osler and Rime, 2020). The FX market is a two-tier market where dealers trade with customers on a bilateral basis, while their trading in the interdealer market reflects private information and residual inventories from trading with customers. Consequently, the interdealer market is the heart of the market and is where price discovery takes place (Bjønnes, Osler and Rime, 2020; Bjønnes, Kathitziotis and Osler, 2022).

III. Documenting price discovery for competing currencies (2003–2007)

For each day in our sample and for each currency, the information and component shares of each rate are computed to deliver daily measures of RILS, RILI and RIS. In addition, daily values of major control variables

8. Wang and Yang (2011), using a sample period that overlaps with ours, find that this period of the daily session dominates the price discovery process for the trading of four major currencies against the USD, including the JPY and the EUR.

describing trading activity, volatility and liquidity are also obtained and their averages are displayed in Table 1. For each currency, the descriptives associated with the EUR rate (EUR/CHF and EUR/JPY for the CHF and the JPY, respectively) and the USD rate (USD/CHF and USD/JPY for the CHF and the JPY, respectively) are presented. The table also displays the corresponding averages for the exchange rate numeraire, that is, the euro-dollar. The most noticeable feature of this summary lies in the substantial difference in liquidity and volatility of the CHF rates. Their values are consistent with a much smaller presence of noise in the EUR rate, which is likely to cause important disagreements between the measures RIS and RILS (and RILI) in their diagnosis of price discovery for the CHF.

Figure 1 presents the evolution of the three measures where monthly averages for the two currencies are displayed in the two graphs. The averages for RILI take only values between 0 and 1 and therefore they lie between the two horizontal lines. They give the proportion of days within each month in which the RILS has a value larger than zero, which in turn can be interpreted as the proportion of such days in which the EUR rate dominates price discovery. The closer these proportions are to one, the more often the EUR rate leads. For the CHF (top graph), there are substantial changes in RILI and RILS over time. The USD rate seems to start serving as the principal vehicle of early information transmission but it loses ground slowly but steadily. By the middle of 2005, the roles have been completely reversed in favor of the EUR rate. However, during the last year and a half, information seems to be arriving at a similar speed in both channels. Table 2 (Panel A) presents statistical evidence confirming these patterns by displaying yearly averages of our measures accompanied by bootstrap bias-corrected 95% confidence intervals. We also report the average for the entire five-year period whose value for RILI is remarkably close to 0.5, summarizing an even evolution of the two rates in the spread of information, although it hides the shifts in leadership that the yearly averages do capture. As for the JPY, both Figure 1 (bottom graph) and Table 2 (Panel B) consistently describe an evolution which is characterized by a strong dominance of the USD rate, especially after 2003.

TABLE 1. Average Daily Trading Activity and Liquidity (January 2003- December 2007)

	CHF		EUR/USD	JPY	
	Euro	Dollar	(Numeraire)	Euro	Dollar
#l. Orders (000's)	6,932	11,854	18,332	11,861	13,165
Volume (bill.$)	2,955	2,214	4,583	2,481	2,840
Bid-Ask Spread (bps)	1,032	1,861	0,886	1,764	1,205
Volatility (%)	4,664	12,861	11,380	10,594	11,165

Note: For each exchange rate, this table displays daily averages of trading activity and liquidity using data from EBS. Only the time interval 8:00-16:00 (GMT) during US winter time and 7:00-15:00 (GMT) during US summer time is considered on each date. Weekends and major US holidays are excluded. #l. Orders (000's) reports the number of limit orders, that is the number of quote revisions at the top of the book. volume (bill.$) displays traded volume in USD billion. bid-ask spread (bps) reports average bid-ask spread in basis points (that is, ask minus bid divided by midquote times 10,000). volatility (%) is computed as the annualized standard deviation of five-minute returns.

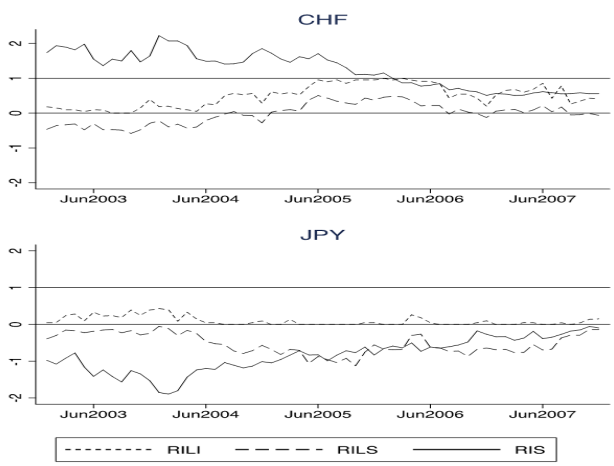

FIGURE 1.— Monthly average over the years 2003-2007 of the daily relative information leadership index (RILI), relative (log ratio of Euro rate to Dollar rate of) information leadership share (RILS) and relative (log ratio of Euro rate to Dollar rate of) information share (RIS) for the Swiss Franc (top) and the Japanese Yen (bottom).

TABLE 2. Average Daily Price Discovery (January 2003-December 2007)

Year	RILI	RILS	RIS
Panel A: Swiss Franc			
2003	0.081	-0.423	1.689
	(0.052, 0.125)	(-0.464, -0.387)	(1.643, 1.737)
2004	0.292	-0.205	1.726
	(0.240, 0.360)	(-0.251, -0.151)	(1.670, 1.780)
2005	0.798	0.274	1.437
	(0.754, 0.849)	(0.173, 0.328)	(1.383, 1.485)
2006	0.724	0.201	0.789
	(0.668, 0.784)	(0.164, 0.238)	(0.762, 0.821)
2007	0.548	0.056	0.563
	(0.480, 0.605)	(0.033, 0.082)	(0.546, 0.578)
All	0.498	0.056	1.241
	(0.470, 0.525)	(0.032, 0.082)	(1.209, 1.274)
Panel B: Japanese Yen			
2003	0.206	-0.218	-1.122
	(0.157, 0.258)	(-0.249, -0.186)	(-1.269, -1.171)
2004	0.120	-0.435	-1.341
	(0.084, 0.164)	(-0.481, -0.390)	(-1.388, -1.282)
2005	0.012	-0.848	-0.829
	(0.000, 0.024)	(-0.886, -0.806)	(-0.867, -0.796)
2006	0.040	-0.630	-0.544
	(0.020, 0.072)	(-0.670, -0.581)	(-0.578, -0.512)
2007	0.020	-0.505	-0.263
	(0.008, 0.044)	(-0.539, -0.469)	(-0.286, -0.241)
All	0.095	-0.528	-0.840
	(0.081, 0.113)	(-0.549, -0.507)	(-0.866, -0.811)

(Continued)

TABLE 2. (Continued)

Note: For each exchange rate, this table displays daily averages of our measures of price discovery for the Swiss Franc and the Japanese Yen using data from EBS. Only the time interval 8:00–16:00 (GMT) during US winter time and 7:00–15:00 (GMT) during US summer time is considered on each date. Weekends and major US holidays are excluded. For each year, Panel A displays the values associated with the Swiss Franc, while Panel B displays the values associated with the Japanese Yen. The second column shows the relative information leadership indicator (RILI). This variable takes the value one if the information leadership share (ILS) is bigger for the euro rate than ILS for the US dollar rate. The third column shows the relative information leadership share (RILS), which is the log of ILS for the euro rate minus the log of ILS for the dollar rate. Similarly, the fourth column shows the relative information share (RIS), which is the log of information share (IS) for the euro rate minus the log of IS for the dollar rate. The numbers in parenthesis below the averages show bootstrap bias-corrected 95% confidence intervals.

The picture portrayed by the measure based on Hasbrouck's information share, RIS, is quite different. For the CHF, its values are well above zero during the entire period, suggesting that price discovery is overwhelmingly dominated by the EUR rate. For the JPY, although the diagnosis is qualitatively similar, RIS establishes that the overall leadership of the USD rate is at its peak during the first two years, in clear contrast with the quantification based on RILI and RILS. As anticipated above, this disagreement is likely to be driven by an uneven presence of noise in the two competing rates. A look at the correlation over the entire period of the daily difference between RILS and RIS and the relative bid–ask spread confirms this presumption since its values are equal to 0.874 and 0.877 for the CHF and the JPY, respectively.[9] [10]

9. For the sake of brevity, we skip a more detailed examination of the drivers of this disagreement. A thorough analysis in the context of equity and options can be found in Patel et al. (2020). Also, Dimpfl and Peter (2021) study the price discovery contributions of cryptocurrency exchanges in the presence of microstructure noise.

10. In what follows, all uses of the word relative, unless otherwise specified, will describe the value of a particular variable associated with the EUR rate in comparison with its counterpart with the USD rate. In our empirical work, this will be quantified with the same logic as the one delivering RILS and RIS, that is, as the log ratio of the value associated with the EUR rate to the one associated with the USD rate.

IV. The drivers of price discovery

It is time now to examine how differences in liquidity, volatility, market trading activity and market-making activity determine the daily evolution of price discovery.[11] Our analysis in this section should not be interpreted as a search for claims of causality but rather as a search for claims of co-movement. We follow Chakravarty, Gulen and Mayhev (2004) and Patel et al. (2020) and run the following OLS regression separately for each one of the two currencies

$$y_t = a_0 + a_1 rbas_t + a_2 rvol_t + a_3 rlim_t + a_4 rvolume_t + b'X_t + \varepsilon_t \quad (4)$$

where $rbas_t$, $rvol_t$, $rlim_t$, and $rvolume_t$ denote log ratios of the daily values of the average bid–ask spread (ask minus bid divided by midpoint), volatility (standard deviation of five-minute returns), number of limit orders (number of revisions at the top of the book), and traded USD volume, respectively, at day t. Our main variables are standard measures of market quality, which are incorporated in studies of price discovery. The dependent variable y_t can be the daily values of any of the three measures of price discovery: RILI, RILS, and RIS.In addition, we control for general market conditions known to affect FX liquidity (see Karnaukh, Ranaldo, and Söderlind, 2015) by adding the log of the VIX index, the log of the volatility of the euro-dollar, and the log of its bid–ask spread. The vector also includes month × year fixed effects.

The role of relative liquidity is in principle uncertain from a theoretical point of view. If the probability of informed trading increases in a given currency pair, market makers may react by widening the spread because of their fear of being adversely selected, as in Glosten and Milgrom (1985). On the other hand, the liquidity hypothesis predicts that informed traders will choose the most liquid market to minimize the price impact of their trades (Fleming, Ostdiek and Whaley, 1996.) and such trading would imply that price discovery increases with tighter spreads. Once again, there is room for disagreement across our measures of price discovery, given that RIS favors a smaller relative presence of noise. This may translate into disparities in the effects of liquidity and volatility on RIS as opposed to RILI and RIS.

The spread may also reflect inventory management and not just

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11. We will address the question of causality in the next section.

adverse selection and order processing costs (Copeland and Galai, 1983 and other papers). Inventory management may affect the size of the spread, or may have temporary effects (intraday) on exchange rates through shading of the midpoint. Inventory management may thus increase noise. Previous studies using data from interdealer markets (e.g. Bjønnes and Rime, 2005, and others), however, provide little evidence of inventory management on the bid–ask spread in FX interdealer markets. These studies suggest that asymmetric information is important in addition to order processing costs (see for instance Bjønnes and Rime, 2005). As to relative trading volume, it seems reasonable to hypothesize that it should contribute to a larger RIS. Finally, one could speculate that a larger number of limit orders will go hand in hand with informational leadership since a leading quote is bound to adjust less than a lagging one. Quoting activity will most likely increase with trading activity and with greater use of autoquotation algorithms. The regression accounts for increases in trading activity by controlling for volume. Greater use of autoquotation algorithms for an exchange rate may be associated with more quoting activity, and may be evidence that the exchange rate follows the synthetic rate. More frequent quote changes may thus be associated with decreased price discovery as suggested by Patel et al. (2020).

Table 3 presents the results of running the regressions in (4). The left (right) three-column block presents the results for the CHF (JPY). For each measure, we find quite consistent results across the two currencies with coefficients and significances that are quite similar in most cases. Out of all control variables, relative volume displays the most robust connection with price discovery since its coefficient displays a significant and positive coefficient across all specifications. The more a rate dominates traded volume, the more informational advantages seem to be present. Relative volatility is significant only when price discovery is proxied by RIS and its effect is negative. This is consistent with this measure strongly weighting the avoidance of noise. Also, quite consistent with our expectations is the evolution of the relative number of quote revisions and relative informational vehicles.

TABLE 3. Daily Co-movement of Price Discovery and Liquidity, Volatility, and Market Activity

	CHF			JPY		
	RILI	RILS	RIS	RILI	RILS	RIS
Rbas	0.499***	0.908***	-1.524***	0.769***	1.024***	-1.187***
	(3.486)	(7.429)	(-11.556)	(4.452)	(5.938)	(-7.589)
Rvol	-0.052	-0.112	-0.244***	0.087	-0.028	-0.249***
	(-0.622)	(-1.553)	(-3.963)	(1.385)	(-0.559)	(-4.326)
Rlim	-0.485**	-0.299*	-0.550***	0.048	-0.236	-0.968***
	(-3.080)	(-2.178)	(-5.691)	(0.333)	(-1.499)	(-8.552)
Rvolume	0.623***	0.558***	0.206***	0.212**	0.484***	0.357***
	(6.696)	(10.383)	(4.231)	(3.116)	(7.648)	(6.579)
lvol_ed	-0.048	-0.116	-0.014	-0.097*	-0.092*	-0.038
	(-0.564)	(-1.513)	(-0.314)	(-2.146)	(-2.044)	(-0.856)
lbas_ed	0.003	-0.021	-0.032**	0.016	-0.010	-0.048**
	(0.174)	(-1.376)	(-2.870)	(0.976)	(-0.606)	(-3.107)
lvix	0.027	0.052	0.084***	-0.018	-0.022	0.056***
	(0.728)	(1.639)	(3.986)	(-0.698)	(-0.799)	(2.812)

Note: Using data from EBS, this table displays the results of regressions where the dependent variable is the daily values of three measures of price discovery: relative information leadership share (RILS), relative information leadership index (RILI), and relative information share (RIS). The main explanatory variables are the daily relative average bid-ask spread (ask minus bid divided by midpoint times 10,000; rbas), volatility (annualized standard deviation of five-minute returns; rvol), number of limit orders (number of quote revisions at the top of the book; rlim), and traded dollar volume in USD billion (rvolume). Except for RILI, relative should be understood as the log ratios of the corresponding variable. In these ratios, the value of the variable for the euro rate is in the numerator, whereas its counterpart for the dollar rate is in the denominator. Additional controls are the log of the volatility of the Eurodollar (lvol_ed), the log of its bid-ask spread (lbas_ed), and the log of the VIX index (lvix). The regressions also include month x year fixed effects. The first and second three-column blocks present the results for the Swiss Franc and Japanese Yen, respectively. Only the time interval 8:00-16:00 (GMT) during US winter time and 7:00-15:00 (GMT) during US summer time is considered on each date. Weekends and major US holidays are excluded. t-statistics in parentheses are calculated based on Newey-West robust standard errors correcting for heteroscedasticity and autocorrelation with 15 lags.

Perhaps the most striking result is the strong significance of the relative bid–ask spread but most importantly, the discrepancy in the sign of such strong co-movement. Indeed, if dominance in price discovery is merely understood as the fastest impoundment of information (RILI and RILS), it seems like a larger bid–ask spread of the EUR rate tends to go together with an increase in its relative leadership. This finding would be consistent with an equilibrium where market makers manage to impose relatively larger spreads to attenuate the potential harm of informed trading. When RIS proxies for price discovery, the results depict a scenario compatible with informed traders moving towards the market that offers better liquidity. At the same time, this latter conclusion once again would need qualification given the special treatment that the information share gives to lower market microstructure noise.

Although volume has been used as a proxy for liquidity in several studies (e.g. Patel et al., 2020), there are also alternative liquidity measures. A popular alternative is the Amihud illiquidity measure, which is volatility (absolute return) divided by volume (Amihud, 2002). As a robustness check we include the Amihud illiquidity measure in regression (4).[12] The results are similar to the results in Table 3, and the coefficients on the relative Amihud illiquidity measure are insignificant (see Appendix, Table A1). We thus conclude that the variables in our original regression (4) already capture the information in the Amihud illiquidity measure.[13]

Studies pursuing the drivers of price discovery abound.[14] However, most of them are likely to be of limited use in establishing a comparison with the results of this section. First, the large majority of them base their analysis on IS (or modifications with a similar logic). This approach may not necessarily be a problem when comparing price processes with similar amounts of noise, as in the case of cross-listed stocks in different venues, but it certainly creates concern in the case of a comparison of spot and derivatives markets if the goal is to establish information

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12. We use exchange rates quoted on noon New York time to calculate absolute return.

13. We also considered potential problems with non-stationarity when using volume in regression (4). To evaluate potential issues with non-stationarity, we perform unit root tests. We run Augmented Dickey-Fuller tests with trend and 10 lags for the variables volume (rvolume) and the Amihud illiquidity measure (ramihud). All tests clearly reject the null hypothesis of one unit root. The results are also robust with respect to trend or no trend, and the number of lags. Using Phillips-Perron tests instead of Augmented Dickey-Fuller tests do not change the rejection results.

14. For a detailed discussion of the studies mentioned, refer to Appendix.

leadership.[15] Second, our framework is novel and it does not conform to any of the ones presented in previous studies since, even though it does involve the use of no-arbitrage relationships, it does not examine the price of the same asset (or directly an asset and its replica) in different venues. Nevertheless, given our use of ILS, a plausible comparison may be Hauptfleisch, Putniņš and Lucey (2016) examining leadership in the price of gold in spot and futures markets, and, especially, Patel et al. (2020), whose focus is on price discovery in stock versus options markets, with the added benefit that this focus also requires the use of implied (synthetic) prices and that they also contrast their results with the alternative use of IS.[16]

As it turns out, results of the latter study are strikingly similar to our results. In particular, they find the same discordant behavior of the relative bid–ask spread and price discovery depending on the particular measure used. Price discovery shows a positive relationship with such a spread when the measures that emphasize leadership are used, whereas this relationship turns negative if RIS is the dependent variable instead. Also, relative volatility, volume and quote revisions drive RILI in a manner that is completely consistent with their results. The only discrepancy with our findings is perhaps the behavior of relative volume and volatility with RIS.[17]

V. Price discovery and managed exchange rate regimes: The SNB peg

On September 6, 2011, as the appreciation pressure on the CHF kept mounting due to the EUR sovereign-debt crisis, the Swiss National Bank (SNB) made public its plans to defend a lower bound on the EUR/CHF of 1.2 with "the utmost determination." The peg had as its goal protecting

15. Putniņš (2013) makes this point and goes on to revisit some of the studies whose claims about information leadership may be unfounded. Hauptfleisch, Putniņš and Lucey (2016) do examine leadership in the price of gold in spot and futures markets.

16. Hauser, Kedar-Levy and Milo(2022) study price discovery during parallel stocks and options markets' preopenings using an alternative approach.

17. For the sake of comparison with Chakravarty, Gulen and Mayhev (2004), these authors do not include the relative number of quote revisions as a control variable in the model where the information share is the dependent variable.

the bulk of Swiss exports and avoiding a recession that might result from an uncontrolled appreciation of the CHF. Although the literature is large regarding theoretical and empirical studies evaluating the economic and financial consequences of departures from free-float exchange rate regimes (see e.g. Fischer, 2001; Levy-Yeyati and Sturzenegger, 2003), little, if anything, is known about their potential effect on the transmission of information. As it turns out, via our novel framework, we find ourselves in a privileged position to present an investigation, albeit only empirically, of such a potential impact. For this purpose, we will use as an identification strategy a differences-in-differences analysis that uses the JPY as a control. Our analysis will use four months of data before and after the implementation of the peg. Unfortunately, our intraday data do not cover the period between May and December 2011. This gap may not be so problematic given that the long-term effect of the peg may not be reached immediately after its imposition, thereby making it desirable to avoid using data immediately after its imposition. In any case, our data are located at a symmetric distance from the peg date. For this new two-period sample, averages for the same variables as in Table 1 are reported in Table 4.

Figure 2 shows the trajectory of the EUR/CHF for the time period starting on January 2, 2011 and ending on April 30, 2012. Our data cover the first and last four-month intervals within that period. Witness the significant change in the volatility of the rate between these two periods, a point which will deserve our attention later in this section. The dashed horizontal line marks the implementation of the peg.

TABLE 4. Average Daily Price Discovery and Market Activity around the SNB's Peg

	CHF			JPY		
	Euro	Dollar	Relative	Euro	Dollar	Relative
Panel A: January 1, 2011-April 30, 2011 (#obs = 82)						
#l. Orders (000's)	90.077	84.195	0.048	113.445	100.524	0.131
Volume (bill. $)	5.071	5.257	-0.046	4.823	12.140	-0.938
Bid-Ask Spread (bps)	2.300	2.179	0.056	2.210	1.445	0.435
Volatility (%)	13.626	14.897	-0.085	14.815	11.472	0.267
IS	0.461	0.535	-0.155	0.276	0.781	-1.060

(Continued)

TABLE 4. (Continued)

	CHF			JPY		
	Euro	Dollar	Relative	Euro	Dollar	Relative
Panel B: January 1, 2012-April 30, 2012 (#obs = 82)						
ILS	0.320	0.397	-0.217	0.218	0.595	-1.006
ILI	0.000	0.072	0.241	0.000	0.820	0.000
#l. Orders (000's)	40.312	74.421	-0.648	97.384	74.566	0.260
Volume (bill. $)	2.870	3.456	-0.233	3.867	9.189	-0.856
Bid-Ask Spread (bps)	1.022	1.832	-0.657	2.291	1.104	0.644
Volatility (%)	3.209	12.595	-1.519	14.925	9.601	0.477
IS	0.822	0.235	1.263	0.205	0.853	-1.436
ILS	0.339	0.243	0.330	0.198	0.621	-1.153
ILI	0.036	0.012	0.771	0.012	0.843	0.012

Note: For each exchange rate, this table displays averages of our three proxies for price discovery using data from EBS. Only the time interval 8:00-16:00 (GMT) during US winter time and 7:00-15:00 (GMT) during US summer time is considered on each date. Weekends and major US holidays are excluded. Columns 2-4 display values associated with the Swiss Franc, while columns 5-7 correspond to the Japanese Yen. The Euro (Dollar) rate is the exchange rate of the Euro (Dollar) with each one of the two currencies (CHF and JPY). For each variable and currency, the table displays its value associated with each one of the two rates in the first two columns whereas the last one presents the relative value. Except for the value associated with the information leadership indicator (ILI), relative should be understood as the log ratios of the corresponding variable. In these ratios the value of the variable for the euro rate is in the numerator whereas its counterpart for the dollar rate is in the denominator. #l. Orders (000's) reports the number of limit orders, that is the number of quote revisions at the top of the book. volume (bill.$) displays traded volume in USD billion. bid-ask spread (bps) reports average bid-ask spread in basis points (that is, ask minus bid divided by midquote times 10,000). volatility (%) is computed as the annualized standard deviation of five-minute returns. The last three rows, correspond to three measures of price discovery: the information share (IS), the information leadership share (ILS) and the information leadership index (ILI). For the ILI variable, the value associated with the Euro (Dollar) rate is 1 if the information leadership share of the Euro (Dollar) rate is greater than 0.5, whereas the variable in the column relative takes value one whenever the former share is greater than the latter and zero, otherwise. (*p<0.05, ** p<0.01, *** p<0.00).

Figure 2 shows the trajectory of the EUR/CHF for the time period starting on January 2, 2011 and ending on April 30, 2012. Our data cover the first and last four-month intervals within that period. Witness the significant change in the volatility of the rate between these two periods, a point which will deserve our attention later in this section. The dashed horizontal line marks the implementation of the peg. The results of our differences-in-differences exercises are reported in Table 5 in its top panel. Only the estimated coefficient of the dummy variable

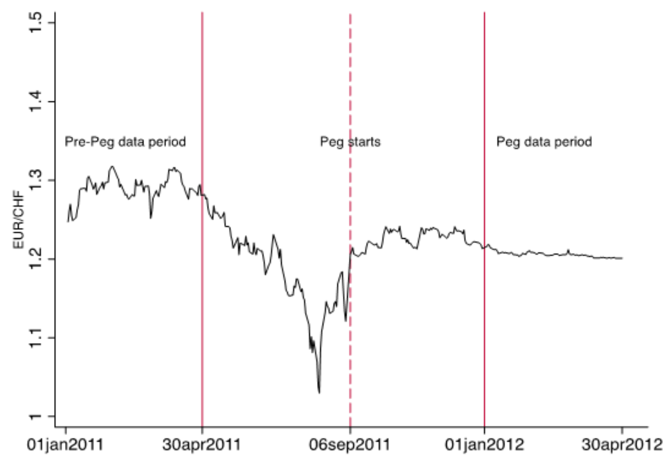

FIGURE 2.— Evolution of the EUR/CHF around the implementation of the SNB's peg.

is displayed. Such an estimate is significant at the 0.1% level for all three relative measures. For RILS and RIS, this significance seems to be driven by both an increase in the share of the EUR rate and a decrease in its USD counterpart.[18] Our findings seem to provide strong evidence suggesting that the SNB peg did raise the informational dominance of its target rate. Hence, informed traders appeared to have flocked towards the EUR rate when trading on any news about the fundamentals of the Swiss economy. One source of concern that may put this conclusion into question is the above-mentioned disparity in the volatility of the EUR/CHF across the two periods in our sample. This massive drop in such volatility, from 13.6% down to 3.2% after the implementation of the peg is a well-known effect of the introduction of a managed regime,

18. The dependent variable in the regressions associated with the EUR rate and the USD rate for the ILI measure is a dummy variable taking value 1 if the corresponding information leadership share is greater than 0.5, and 0 otherwise. However, RILI takes value one if the information leadership share of the EUR rate is greater than its USD counterpart, and zero otherwise. Hence, the resulting estimated coefficients and their significance for these two regressions may be uninformative (as in this case) in explaining the change in RILI.

an effect which is called the “honeymoon effect.”[19]

To remove any potential weekly or monthly seasonalities that could affect our results, the potential impact is estimated by a direct examination of the differences. Specifically, for our three measures of price discovery, RIS, RILS and RILI, we associate their values on each date in 2012 with those on a date, and only one date, in 2011 which happens to be on the same day of the week. In particular, if the former, falls for example on a Monday and this happens to be the nth Monday of 2012, the difference of the outcome variable is computed with respect to its value on the nth Monday of 2011.[20] Apart from the impact of the peg on relative price discovery, we also examine its effect on the level of their two individual components associated, respectively, with the EUR rate and USD rate. Each one of these differences, for the three outcome variables and the individual shares (or indicators) of the EUR and the USD rates, are regressed on a constant and a dummy variable flagging the observations associated with the CHF. Figure 3 displays the evolution of RILS and RIS for the two periods in our sample and the two currencies. Their behavior does not seem to display a serious

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19. Krugman (1991) presents a seminal contribution in the investigation of the behavior of exchange rates under target zones. The exposition relies on a very simple model where the dynamics of the (log) exchange rate are broken into the sum of two components. The first one represents the fundamentals, that is, a comprehensive aggregation of all those variables that are supposed to determine the evolution of the rate under a free-float regime. The money supply, which is under the complete control of the central bank, is one of those variables, although the fundamentals also include economic and geopolitical elements which are beyond the control of such an institution. The expected deviation of the exchange rate from those fundamentals is assumed to be zero under a free-float regime. The crucial element in the model is a second component which represents the (nonzero) predictable change in the exchange rate due to the existence of a target zone. The idea here is that market players know that the bank will intervene if the exchange rate hits the upper or lower bound. In particular, the expected change in the value of this rate will be (negative) positive when it hits the (upper) lower bound. A pivotal assumption is that all agents deem the defense of the level of the rate by the bank as perfectly credible and effective. As it turns out, even if it is further assumed, as the model does, that the intervention happens only at the margin, that is, when the rate is arbitrarily close to the edges of the target zone, the remarkable prediction is that the simple announcement of a target zone delivers an automatic stabilization, not only for values of the exchange rate that are very near those edges but also for values of such rates that lie well within this zone. It is this general reduction in volatility, whose intensity is magnified as the rate gets closer to its limiting bands, which it is known as the honeymoon effect.

20. If one of the two associated dates falls on a holiday, we remove their difference from our analysis.

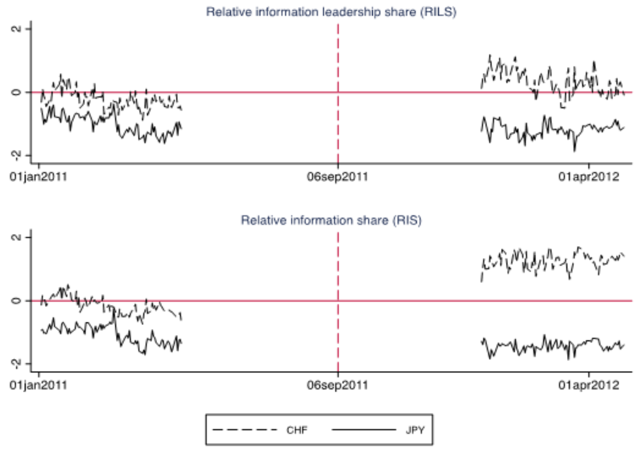

FIGURE 3.— Evolution of the relative (log ratio of Euro rate to Dollar rate of) information leadership share (RILS) and information share (RIS) for the Swiss Franc and the Japanese Yen around the implementation of the SNB´s peg

violation of the parallel-trend assumption. Table 5 also shows the results of applying our differences-in-differences analysis to relative volatility and to the bid–ask spread. The evolution of these two variables is also displayed in Figure 4. We can safely conclude that the drop in volatility is caused by the implementation of the peg.[21] Note that this drop leads to a move from a situation in which both the EUR and the USD rates for the CHF have similar variability to a new scenario in which the former is clearly less volatile. Once again we find ourselves confronted by potential asymmetric levels of noise which may bias our measures. Although unlikely, it could be argued that this difference in volatility does not necessarily have to correspond to a disparity in the presence of noise (microstructure frictions or illiquidity). However, Tables 4 and 5 also show that the bid–ask spread of the EUR rate plummeted after the introduction of the peg, clearly affecting the balance of liquidity between

21. Given that the EUR/CHF finds itself very close to the band during a large part of the period that we examine, our result by itself does not confirm the existence of a honeymoon effect. However, Lera and Sornette (2016) have concluded that the SNB peg has been a case were both assumptions of the Krugman model "apply sufficiently well" and they find strong evidence of such an effect.

the two rates associated with the CHF. In principle, RILS and RILI are especially conceived to address the potential biases that this asymmetry may bring, but the concern is still worth considering given the prominent size of the difference in the relative levels of noise between the two periods (Yan and Zivot, 2010; Putniņš, 2013; Patel et al., 2020).

TABLE 5. Differences-in-differences Analysis of the SNB peg

	Euro rate	Dollar rate	Relative
IS	0.435***	-0.372***	1.801***
	(12.949)	(-23.053)	(18.154)
ILS	0.049**	-0.190***	0.753***
	(2.656)	(-11.386)	(8.561)
ILI	0.037	-0.100	0.550***
	(1.867)	(-1.651)	(9.403)
bid-ask spread (bps)	-1.147***	-0.110	-0.895***
	(-10.705)	(-1.311)	(-11.013)
volatility (%)	-10.716***	-0.488	-1.635***
	(-17.751)	(-0.854)	(-25.609)
Observations	160	160	160

Note: This table uses data from EBS. Only the time interval 8:00-16:00 (GMT) during US winter time and 7:00-15:00 (GMT) during US summer time is considered on each date. Each date between January 1, 2012, and April 30, 2012, excluding those of low trading activity (weekends and national US holidays), is associated with one and only one similar date in 2011. In particular, both dates must correspond to the same day of the week with equal ordering within the year. Differences are then computed between those two dates for the euro rate, dollar rate, and log ratio of the following variables: average bid-ask spread (ask minus bid divided by midpoint times 10,000), volatility (annualized standard deviation of five-minute returns), information share, and information leadership share. The information leadership index is also examined. In this case, the value associated with the Euro (Dollar) rate becomes 1 if the information leadership share of the Euro (Dollar) rate is greater than 0.5, whereas the variable in the column relative takes value one whenever the Euro rate's share is greater than the Dollar's and zero otherwise. Each of these sets of differences (three for each variable) is then regressed on a dummy taking value one or zero if the associated currency is the Swiss Franc or the Japanese Yen, respectively. Newey-West standard errors accounting for heteroskedasticity and autocorrelation are used (lag equal to 5). The table reports for each regression the coefficient of the dummy variable, while its associated t-ratio is reported in parentheses. (* $p<0.05$, ** $p<0.01$, *** $p<0.001$).

One possible way to address this issue is to resort to a two-stage least squares (2SLS) instrumental variable regression to gauge the impact that the evolution of the bid–ask spread has on our measures of price discovery. The imposition of the lower bound on the EUR/CHF is an obvious exogenous shock that can facilitate this approach. If our

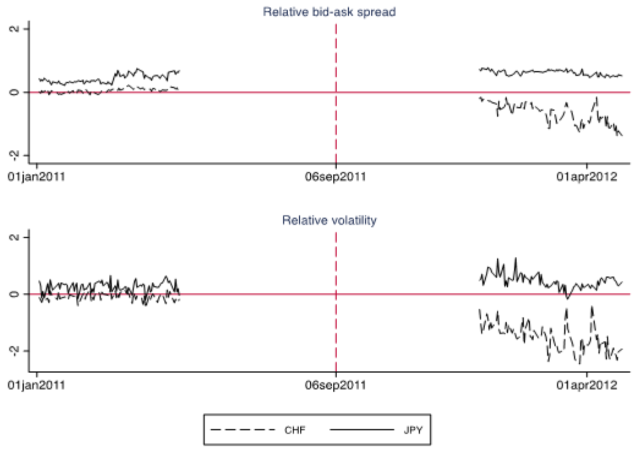

FIGURE 4.— Evolution of the relative (log ratio of Euro rate to Dollar rate of) bid-ask spread and volatility for the Swiss Franc and the Japanese Yen around the implementation of the SNB´s peg

two-stage regression delivers no impact of relative liquidity, our evidence above indicating an increase in the informational advantages of the EUR rate after the SNB policy decision may stand on safer ground. An interesting byproduct of this exercise is to provide additional evidence examining how informed traders' presence in a particular market is affected by relative liquidity. The liquidity hypothesis claims that those traders will opt for the most liquid market and hence, we should observe in our case that relative informational vehicles will be affected by changes in the relative bid–ask spread. Patel et al. (2020), using a change in the minimum tick of options quotes as an instrument, find no support for the hypothesis.

Given the theoretical and empirical evidence around the honeymoon effect, it is relatively safe to presume that the drop in the relative bid–ask spread is actually caused by the drop in relative volatility brought about by the SNB peg. Hence, we could in principle use the latter as an instrument for the former under the assumption that the impact of relative volatility on price discovery exclusively occurs via its impact on relative liquidity (the exclusion restriction). The results of the previous section are compatible with such an assumption. As is shown in Table 3, relative volatility does not seem to co-move with RILS and RILI.

Our instrumental variables analysis thus involves the estimation of the following first-stage regression

$$rbas_t = b_0 + b_1 rvol_t + b_2 rlim_t + b_3 rvolume_t + b_4 rmar_t + c' X_t + \varepsilon_t \quad (5)$$

and the second-stage regression:

$$y_t = a_0 + a_1 rbas_{\text{-fitted\_t}} + a_2 rlim_t + a_3 rvolume_t + a_4 rmar_t + d' X_t + \varepsilon_t \quad (6)$$

where $rbas_t$, $rvol_t$, $rlim_t$, $rvolume_t$, and $rmar_t$ are once again the relative bid–ask spread, volatility, number of limit orders, traded volume in USD billion, and number of market orders, respectively, at day t.

In addition, y_t denotes any of our three proxies for relative price discovery, and $rbas_{\text{-fitted\_t}}$ denotes the fitted values of the dependent variable in the first-stage regression. X_t is an additional vector of control variables that includes a month $\times$ year fixed effect, the log values of volatility and the bid–ask spread of the euro-dollar, and the relative volatility and the relative bid–ask spread associated with the JPY.

The first-stage regression results are listed in the first column of Table 6. As we can see, relative volatility seems to be a strong instrument for relative liquidity. Its coefficient is significant at the 0.1% level. It also displays an expected positive sign connecting a decrease in the variability of the EUR rate with respect to its USD counterpart with a decrease in its relative bid–ask spread. The output of the second-stage regression is shown in the other three columns. As expected, given its proven bias towards avoidance of noise, RIS appears to be affected in a positive way by the decrease in relative liquidity. This impact appears to be less significant when price discovery is measured by RILS and in addition, it switches its sign. No such impact is present when we use RILI. Given the superiority of this latter measure to handle noise biases, our results can be used as evidence against the liquidity hypothesis. Most importantly, since our differences-in-differences analysis delivers a significant increase in RILI, our evidence above suggesting an increased activity of informed traders in the EUR/CHF rate as opposed to the USD/CHF rate appears to prevail.

TABLE 6. Instrumental Variables Analysis of Price Discovery and Liquidity for the CHF around the Implementation of the SNB´s peg

First stage		Second stage		
	rbas	RIS	RILS	RILI
rvol	0.254***			
	(5.916)			
rbas		-0.824***	0.864*	0.435
		(-4.034)	(2.234)	(0.957)
rlim	0.269***	-0.039	-0.493*	-0.282
	(3.430)	(-0.381)	(-2.507)	(-1.166)
rvolume	-0.285*	0.304	1.564***	1.459***
	(-2.229)	(1.454)	(5.162)	(3.628)
lvol_ed	-0.029	0.084	0.055	0.186
	(-0.352)	(0.991)	(0.411)	(0.891)
lbas_ed	0.530*	-0.070	-0.821	-0.904
	(2.421)	(-0.274)	(-1.858)	(-1.739)
rvol_jpy	-0.059	0.110	0.215	0.107
	(-0.911)	(1.288)	(1.597)	(0.884)
rbas_jpy	0.444**	-0.248	-0.784*	-0.623
	(3.288)	(-1.101)	(-2.273)	(-1.418)
lvix	0.137	-0.056	-0.507*	-0.553
	(1.177)	(-0.409)	(-2.274)	(-1.601)
Obs.	164	164	164	164
Adj. R-sq.	0.933	0.949	0.665	0.468

Note: This table uses data from EBS. Only the time interval 8:00-16:00 (GMT) during US winter time and 7:00-15:00 (GMT) during US summer time is considered on each date. The table presents the results of our instrumental variables estimation. The daily values of relative (log ratio of Euro rate to Dollar rate of) volatility are employed as an instrument for those of the relative bid-ask spread. Main control variables are the daily values of the relative number of limit orders, relative traded volume in USD billion, and the relative number of market orders. Additional controls are the daily values of the log of the volatility of the Eurodollar, the log of its average bid-ask spread, the relative volatility and bid-ask spread associated with the Japanese Yen, and the log of the VIX index (lvix). Month x year fixed effects are also included. The results of the first-stage regression are presented in the first column, while the second-stage regression results for relative information share (RIS), relative information leadership share (RILS), and information leadership index (RILI) are displayed in the last three columns. Newey-West standard errors with five lags of the coefficients accounting for heteroskedasticity and autocorrelation are used in all cases, and their associated t-ratios are reported in parentheses. (* $p<0.05$, ** $p<0.01$, *** $p<0.001$).

VI. Discussion and conclusions

Considering the evidence in the previous section suggesting a reduced role for the relative bid–ask spread in the determination of price discovery, we can produce an intriguing implication. As we have indicated earlier in Section 2.1, no-arbitrage requires that

$$I^a_{DC} > A^b_{DC} \qquad I^b_{DC} < A^a_{DC}$$

and that identical constraints should hold for the corresponding EUR rates. Note that even though no-arbitrage is compatible with the violation of the following inequalities:

$$I^a_{DC} > A^a_{DC} \quad \text{and} \quad I^b_{DC} < A^b_{DC}, \tag{7}$$

The vehicleness of a given exchange rate is facilitated whenever these restrictions also hold. Indeed, if the implied bid (ask) rate is larger (smaller) than the actual one, it pays off to use the indirect route to sell (buy) US dollars in exchange for units of currency C. In other words, those actual quotes that do not satisfy these inequalities are likely to be stale, and a stale quote is plainly the opposite of a leading quote. One would thus expect that the more stale the quotes of a given exchange rate are, the less informational advantage the rate has.[22] However, after inspecting the inequalities in (7) again, it becomes evident that wide spreads are more likely to violate these restrictions than smaller spreads are. Hence, insofar as wider spreads empirically tend to correlate with staleness, the small relevance of the bid–ask spread that we found above makes plausible the presumption that staleness has little to do with price discovery.

To investigate this issue further, we construct a measure of relative staleness and examine its correlation with the relative bid–ask spread series used in the previous section. For the two competing exchange rates associated with the CHF and the USD during the same days as the sample employed in the previous section, we compute the percentage of quotes (bid or ask) within our daily interval that violate (7) and compute

22. A stale quote can be defined as an old price of an asset that does not reflect the most recent information (Nasdaq).

the daily values of a measure of relative staleness defined as:

$$\ln S_{e_t} - \ln S_{d_t},$$

where S_{e_t} and S_{d_t} denote staleness measured as the percentage described above for the EUR and the USD rates at day t, respectively.[23] The correlation between this series and the one associated with the relative bid–ask spread is a staggering 0.9788.

As a possible explanation for this result that denies relevance to staleness when it comes to informational vehicleness, it is worth noting that our main arguments in this discussion have relied on a basic assumption. Traders of the EUR (USD) rate may easily avoid bad quotes by trading instead the euro-dollar and the USD (EUR) rate. In particular, it should be possible to execute this alternative strategy at low risk. This is crucial for staleness and price discovery to be connected. Hence, it may be the case that quotes that violate the inequalities in (7) may not be so stale after all. Execution risk and residual risk may protect their usefulness to traders. A full inquiry into these issues is, however, beyond the scope of this investigation and is possible material for further research. For instance, a more formal analysis of price discovery using the measure of relative staleness may follow the methodology used by Muravyev, Pearson, and Broussard (2013), and later by Patel et al. (2020).

The approach employed in this paper is simple and exploits the clear domination of currency markets by the USD and the EUR. Hence, for

23. We calculate S_{et} and S_{dt} in the following way: For each competing currency, we check the proportion of times the bid or the ask violates the inequalities in (7). We next compute the relative value of this proportion. For example, suppose that for date t there are 10,000 observations in book time for the EUR/CHF ask, and to make things simple, the same number for the bid. Also assume for simplicity the same number for the USD/CHF bid and for the ask. We look at every one of these observations and suppose that 5,600 asks and 3,500 bids violate the constraints for the EUR/CHF and 2,500 asks and 3,000 bids violate the constraints for the USD/CHF. We can then calculate S_{et} and S_{dt}:

$$S_{et} = \frac{5,600 + 3,500}{10,000 + 10,000} = 0.455$$

$$S_{dt} = \frac{2,500 + 3,000}{10,000 + 10,000} = 0.275$$

For date t, the relative measure of staleness is computed as:

$$\ln(S_{et}) - \ln(S_{dt}) = \ln(0.455) - \ln(0.275) = 0.504$$

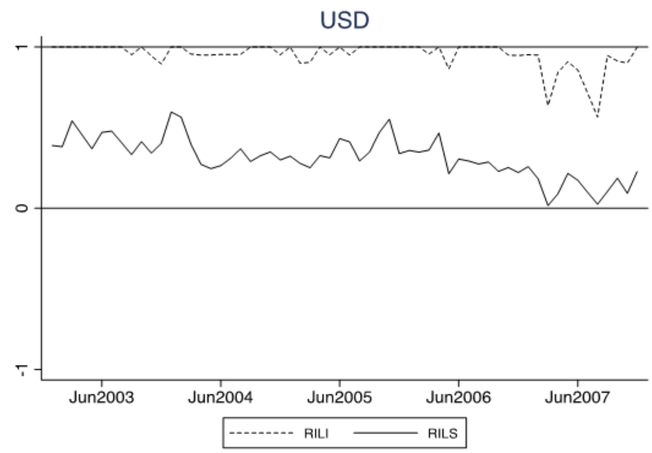

FIGURE 5.— Monthly average over the period January 1, 2003-December 31, 2007 of the daily relative information leadership index (RILI) and the relative information leadership share (RILS) for the EUR/USD vs. USD/JPY (the cross rate EUR/JPY works as reference point).

any country whose official legal tender is neither of them, the trading of news on the fundamentals of its economy is mostly channeled via its currency's exchange rate with either one of the dominating ones. This setup also uses an exchange rate numeraire, the euro-dollar, which has the flavor of a common reference point facilitating the comparison of the two competing exchange rates.

Our framework also has the benefit that it can be easily tweaked to examine exchange rate numeraire competition where, for example, the EUR/USD can be challenged by the USD/JPY rate and their common reference point is played by the cross rate, that is, the EUR/JPY currency pair. This exercise has an interesting economic interpretation. The two rates can be presented as two competing channels to trade news about the fundamentals of the US economy. Furthermore, and accepting the USD as the main currency numeraire, this redesign allows us to present these channels as trading vehicles of information about the fundamentals of the world economy. Alternatively, this whole endeavor could be seen as introducing a third currency numeraire competing for the numeraire status of the EUR. As an example of the feasibility of this approach, Figure 5 presents the monthly average of RILI and RILS in this case. The EUR/USD seems to absorb faster any information about the (world) US economy. The yearly average of RILI for all our data, including those from the four months of both 2011 and 2012, is always above 0.97, with the exception of only 2007, where the corresponding average is 0.8427. A more careful empirical analysis at this point may be deemed less interesting given the clear domination of the EUR/USD. The rise of China, with the potential loss of the economic relevance of the eurozone, may however increase the relevance of any future use of this tool.

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Appendix

Let v be the (unobserved) efficient value underlying the two prices in two different markets of the same asset. Denote them by p_1 and p_2, respectively.[24] We will assume that we can write

$$p_t \equiv \begin{bmatrix} p_{1t} \\ p_{2t} \end{bmatrix} = \begin{bmatrix} v_t + e_{1t} \\ v_t + e_{2t} \end{bmatrix} \tag{8}$$

and

$$v_t = v_{t-1} + u_t,$$

where u_t is assumed to be zero-mean and serially uncorrelated. The other error terms e_{st} and $e_{\iota t}$ are zero-mean with a k-th order auto-covariance matrix that depends only on k. Then, by the Granger representation theorem, the two cointegrated rates obey a VECM specification which has the form

$$\Delta p_t = \alpha\beta' p_{t-1} + \sum_{i=1}^{M} B_i \Delta p_{t-i} + \epsilon_t, \tag{9}$$

where α and β are two-dimensional vectors containing the error correction and cointegrating terms, respectively. The M 2×2 matrices B_i contain coefficients determining the short-term dynamics of the process, and ϵ_t is a two-dimensional vector of serially uncorrelated error terms whose variance-covariance matrix will be denoted by

$$\Omega = \begin{bmatrix} \sigma_1^2 & \sigma_{12} \\ \sigma_{12} & \sigma_2^2 \end{bmatrix}.$$

Furthermore, since the two prices are directly comparable, it follows that $\beta = [1, -1]$. By following Hasbrouck (1995) and Baillie et al. (2002), it can be proved that the variance of the innovation to the efficient value is given by $\psi'\Omega\psi$ where ψ is a 2-dimensional vector which is proportional to $\alpha_\perp = [\gamma_1, \gamma_2]$, an orthogonal vector to α. If the covariance σ_{12} can be assumed to be zero, one can obtain the information share of the actual and implied rates in a straightforward

24. In our case, the two prices will correspond to an observed exchange rate and its associated implied rate as we will see later.

manner by computing the ratios

$$IS_i = \frac{\gamma_i^2 \sigma_i^2}{\gamma_1^2 \sigma_1^2 + \gamma_2^2 \sigma_2^2}, \quad i = 1, 2.$$

However, the two error terms in ϵ_t are likely to be correlated. In such a case, we can consider the Cholesky decomposition $\Omega = FF'$ where it is easy to confirm that

$$F = \begin{bmatrix} \sigma_1 & 0 \\ \rho\sigma_2 & \sigma_2\sqrt{1-\rho^2} \end{bmatrix},$$

with ρ denoting the correlation between the two error terms in ϵ_t. Note also that for the purpose of the computation of the ratio giving the information share, it is necessary only to specify the values in ψ up to a constant. Hence, we can pick $[\gamma_1, \gamma_2] = [\alpha_2, -\alpha_1]$. One could then compute the two information shares as

$$IS_1 = \frac{\alpha_2^2\sigma_1^2 + \alpha_1^2\sigma_2^2\rho^2 - 2\alpha_2\alpha_1\sigma_{12}}{\alpha_2^2\sigma_1^2 + \alpha_1^2\sigma_2^2 - 2\alpha_2\alpha_1\sigma_{12}},$$
$$IS_2 = \frac{\alpha_1^2\sigma_2^2 - \alpha_1^2\sigma_2^2\rho^2}{\alpha_2^2\sigma_1^2 + \alpha_1^2\sigma_2^2 - 2\alpha_2\alpha_1\sigma_{12}}.$$

However, the order of the two elements in the vector Δp_t becomes consequential since the corresponding information share of the actual rate is different if its associated process is located in the first place. In fact, assuming that the correlation ρ is positive and that the coefficients α_1 and α_2 have different signs,[25] such an information share turns out to be always larger when placed in that position. As a result, although this method does not allow for a direct determination of the information share, it does deliver upper and lower bounds which, in the case of the actual rate, are given by

$$IS_{u1} = \frac{\alpha_2^2\sigma_1^2 + \alpha_1^2\sigma_2^2\rho^2 - 2\alpha_2\alpha_1\sigma_{12}}{\alpha_2^2\sigma_1^2 + \alpha_1^2\sigma_2^2 - 2\alpha_2\alpha_1\sigma_{12}},$$
$$IS_{l1} = \frac{\alpha_2^2\sigma_1^2 - \alpha_2^2\sigma_1^2\rho^2}{\alpha_2^2\sigma_1^2 + \alpha_1^2\sigma_2^2 - 2\alpha_2\alpha_1\sigma_{12}}. \tag{10}$$

Empirically, we proceed by first estimating the model in equation (9) by OLS for a predetermined number of lags chosen by using the Akaike information criterion.[26] An orthogonal vector to $\hat{\alpha}$ is then computed, and $\hat{\Omega}$ follows from the estimated residuals of the two OLS regressions. This delivers all the necessary ingredients to be plugged into the upper-bound and lower-bound formulas of the information share above. More details are provided in the empirical section.

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25. Given the model dynamics, α_1 should be negative and α_2 positive.

26. Lags are computed in book time.

Conveniently, the component share can be produced by exclusively relying on the error correction coefficients. The measure results from computing the ratios

$$CS_1 \equiv \frac{\gamma_1}{\gamma_1 + \gamma_2} = \frac{\alpha_2}{\alpha_2 + |\alpha_1|},$$
$$CS_2 \equiv 1 - CS_1.$$

Footnote 14

A group of them focused on price discovery for the same financial asset across different venues or across different periods of the daily trading season. A second group focused on informational value across spot and derivatives markets. Examples of the former are Frijns, Gilbert and Tourani-Rad (2015) and Eun and Sabherwal (2003), who examine a cross-section of Canadian firms trading on the Toronto Stock Exchange and the NYSE, the NASDAQ and the AMEX. Both studies find a significant effect for both trading volume and liquidity in the direction reasoned above. Also, Ozturk, van der Wel and van Dijk (2017) examine the intraday price discovery of 50 S&P stocks across different US venues and report a significant negative effect of the bid–ask spread, and a negative but weak effect of volatility, whereas trade size displays no coherent pattern. Gau and Wu (2017) apply the logic of the definition of information shares and manage to extend it to evaluate the effect of macroeconomic news on the price discovery for a unique price process of the same exchange rate but across the nonoverlapping trading hours of Tokyo, Europe and the US. For the EUR/USD, liquidity, volatility and volume are found to move in the same direction as price discovery in most of their specifications, while the same holds for the USD/JPY with the exception of liquidity, which moves in opposite ways. Chakravarty, Gulen and Mayhev (2004), on the other hand, examine the information share of options versus their underlying equity to conclude that relative liquidity and volume correlate positively with price discovery in the options market whereas the equity market tends to be favored on days with high stock volatility. Mizrach and Neely (2008) focus their attention on spot and futures markets for US government bonds and Chen and Gau (2010) look at the effect of macroeconomic news on the price discovery shares of the spot and futures markets for the EUR/USD and USD/JPY. Their findings for relative volatility and volume are in line with our speculations above, while the latter study attributes no significance to the relative bid–ask spread and the former estimates a negative coefficient. Volatility and the bid–ask spread also seem to decrease the informational share of equity versus their underlying credit default swaps for US firms, as indicated by Kryzanowski, Perrakis and Zhong (2017). Finally, the effect of the number of limit orders is wildly ignored as a determinant. One of the few exceptions is Frijns, Gilbert and Tourani-Rad (2015) but they find this variable to have no statistical significance.