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Foreign Exchange Interventions and their Impact on Expectations: Evidence from the USD/ILS Options Market[1]

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Abstract

Using confidential daily data, we analyze how the intervention episode of the Bank of Israel (BOI) from 2013 to 2019 has affected the foreign value of the ILS and the expectations about its future value. We find that interventions amounting to USD 1 billion are on average associated with a depreciation of the USD/ILS and the Nominal Effective Exchange Rate (NEER) by 0.82%-0.85%, which is at the upper bound of the estimated impact in other studies. We stress that an intervention of USD 1 billion does not reflect the average daily intervention by the BOI and it serves as a benchmark to compare to other research papers in the field of FX interventions. The (indirect) effect on the forward rate is smaller - the BOI's USD purchases have widened the negative deviation from covered interest parity. The higher moments of the risk-neutral probability distribution (RND) of future exchange rates extracted from USD/ILS options, on the contrary, are unaffected. The USD purchases simply shift the whole RND towards higher USD/ILS values. Crash risk, for instance, is unaffected. We also find that the USD/ILS options market anticipates intervention episodes and prices them in before they occur.

JEL classification: E42, E58, F31, G14, G15.

Keywords: Exchange rate, expectations, central bank intervention, Israeli new shekel, reaction function.

התערבויות במטבע חוץ והשפעתן על ציפיות: עדויות משוק האופציות על השקל-דולר

מרכוס הרטריך ודניאל נתן

תקציר

באמצעות נתונים יומיים חסויים, אנו מנתחים כיצד ההתערבויות של בנק ישראל בשוק המט״ח השפיעו על ערכו של השקל ועל הציפיות לגבי ערכו בעתיד. אנו מוצאים כי התערבות בהיקף של מיליארד דולר גורמות לפיחות של 0.82%-0.85% בשער החליפין של השקל-דולר ושל שער החליפין הנומינלי אפקטיבי. השפעה זאת היא בגבול העליון של ההשפעות הנמצאו במחקרים אחרים. אנו מדגישים כי היקף התערבות של מיליארד דולר אינו משקף את ההתערבות היומית הממוצעת של בנק ישראל והיא משמשת אותנו כדי להשוות לממצאים במחקרים אחרים בספרות בתחום התערבויות בשער החליפין. ההשפעה (העקיפה) של ההתערבות על שער הפורוורד שקל-דולר קטנה יותר—ההתערבויות של בנק ישראל הגדילו את הסטייה השלילית מה-Covered interest rate parity. לעומת זאת, המומנטים הגבוהים של ההתפלגות הנייטרלית לסיכון הנגזרת ממחירי האופציות על השקל-דולר נותרת ללא שינוי. כלומר, ההתערבות של בנק ישראל גורמת לתזוזה של כל ההתפלגות. כך לדוגמה, ההסתברות לייסוף חריג (Crash risk) נותרת ללא שינוי. אנו מוצאים גם כי שוק האופציות שקל-דולר צופה את ההתערבויות של בנק ישראל ומתמחר אותן.

1 Introduction

Since the Great Financial Crisis (GFC), many central banks have adopted an intervention regime in the foreign exchange (FX) market as part of their monetary policy toolkit.[1] While the literature on FX interventions has intensively studied the effect of different intervention regimes on spot FX markets, much less is known about its impact in shaping market expectations as reflected in FX derivatives markets. The few papers that have researched this topic[2] have found only a weak relation between interventions in spot FX markets and their effect on FX derivatives markets. However, if interventions are associated with a significant spot FX rate response, as the literature suggests,[3] the derivative market's perception of the uncertainty concerning the future spot FX rate[4] may also change, as the price of an option is connected to the price of the underlying FX rate.

The apparent disconnect between the spot and derivative markets may also be at odds with the well-known informational efficiency of derivative markets in rapidly incorporating news into prices. For example, Hattori, Schrimpf, and Sushko (2016) analyse the response of the tails of the risk-neutral probability density (RND) function extracted from S&P 500 index options to unconventional monetary policy announcements, focusing on quantitative easing (QE) policies. They find that these announcements significantly reduce option-implied equity market crash risk. This finding and the fact that both QE policies and direct FX interventions significantly affect FX rates in theory and empirically[5] suggest that FX interventions may similarly reduce crash risk in FX option markets.

In this paper, we use Israel as a case study to analyse the effect of the Bank of Israel's (BOI) daily intervention activity – which is confidential data – in the USD/Israeli new shekel (ILS) spot market on the foreign value of the ILS and the USD/ILS options market. In March 2008, the BOI started intervening in the FX market for the first time since 1997[6] by purchasing USD on a frequent basis and sterilising these purchases in the fixed-income market to neutralize the effect that the FX interventions might have on money market rates.[7] As a result of this monetary policy regime switch, the BOI accumulated USD 89.2

[1]See, for instance, Borio and Disyatat (2010) and Domanski, Kohlscheen, and Moreno (2016).

[2]See, for instance, Galati, Melick, and Micu (2005) and Galati, Higgins, Humpage, and Melick (2007).

[3]For example, in a recent meta-analysis Arango-Lozano, Menkhoff, Rodríguez-Novoa, and Villamizar-Villegas (2020) find that a net purchase of USD 1 billion is associated with a contemporaneous depreciation of the domestic currency by 1%.

[4]As reflected in the higher moments (e.g., the variance, skewness and kurtosis) of the risk-neutral probability density of the underlying exchange rate.

[5]See Jarrow and Li (2015) and Dedola, Georgiadis, Gräb, and Mehl (2021) for evidence on the impact of QE policies on FX rates.

[6]The intervention activity that started in 2008 constitutes the first intervention episode of the BOI since the ILS was allowed to float freely from mid-1997 onwards (Elkayam, 2003).

[7]With sterilized interventions, interventions can affect exchange rates via the portfolio and the signaling channel (see Sarno and Taylor (2001) and Villamizar-Villegas and Perez-Reyna (2017)). The former

billion from March 2008 until December 2019, around 23% of Israeli GDP in 2019.

After more than a decade of USD purchases, the question arises of how effective the intervention activity by the BOI has been. We are particularly interested in the response of financial market participants' expectations about the future value of the ILS and its future risk characteristics as reflected in the USD/ILS options market, as the effect of FX interventions on spot FX rates might be short-lived, if expectations do not respond to FX interventions in the intended direction (Miyajima, 2013).[8] Using options market data distinguishes our paper from the work of Ribon (2017) and Caspi, Friedman, and Ribon (2018) who both analyzed how the BOI's USD purchases have affected the foreign value of the ILS in the spot market, while remaining silent about the reaction of the corresponding forward and options market.

To motivate our paper, Figure 1 displays the monthly volume of FX interventions, which is published on a monthly basis, the nominal effective exchange rate (NEER)[9] of the ILS and the USD/ILS exchange rate from January 2008 to December 2019.[10] The figure shows a steep appreciation of the ILS by almost 30% from 2008 until the end of our sample according to the NEER and a 10% appreciation vis-à-vis the USD.[11] In tandem, the bank intervened in the USD/ILS spot market, particularly during periods of strong appreciation pressure. In the period displayed in Figure 1, however, the BOI changed its intervention strategy several times. The BOI even stopped intervening in July 2011 for the following two and a half years. For interested readers, we provide an overview of the six different regimes since 2008 in online Appendix A.

In the present paper, we focus on the intervention regime that was in place from January 2013 until January, 14 2021[12] and was characterized by secret and fully sterilized USD purchases in the USD/ILS spot market. However, we opt to end our sample period

works through the effect of interventions on expected asset returns that may trigger adjustments in the composition of financial market participants' investment portfolios ("portfolio re-balancing"). The latter works through the information and intent that interventions reveal to financial market participants about future changes in the stance of monetary policy. Fanelli and Straub (2021) develop a theory of FX interventions with FX forward guidance where the effect of these two channels is not disentangled.

[8]Dominguez (1986) already emphasized the role of expectations for the determination of FX rates in the aftermath of the Bretton Woods era. The seminal work of Engel and West (2005) develops an asset pricing formula, where the spot FX rate is a function of current and expected future fundamentals, which highlights the prominent role of expectations in affecting spot FX rates.

[9]This index is measured as the geometric average of the ILS exchange rate vis-à-vis 24 currencies representing 31 countries, Israel's major trading partners by proportion of trade (Friedman and Galo (2015) and `https://www.boi.org.il/en/Markets/ExchangeRates/Pages/efectinf.aspx`).

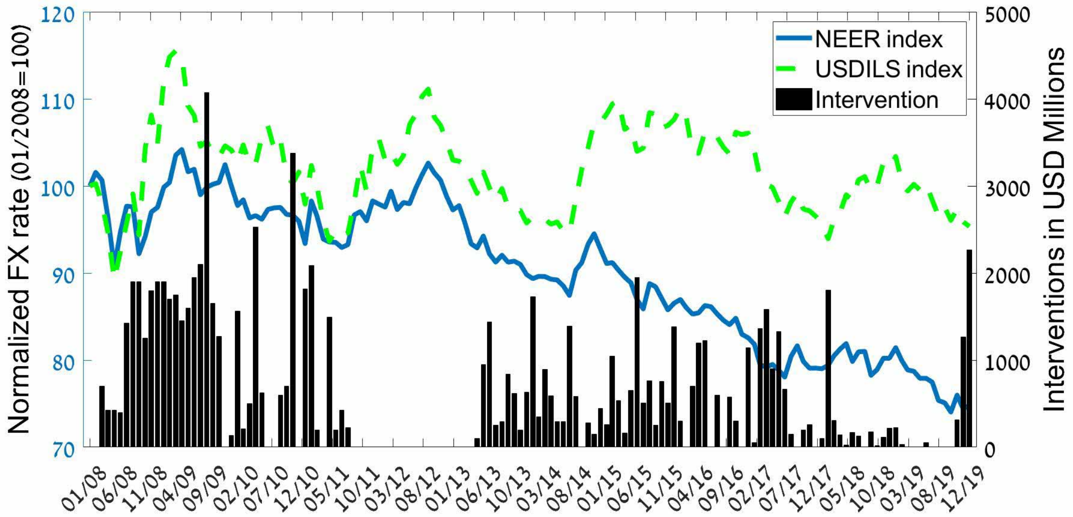
[10]Note that both exchange rates are displayed as an index for the ease of comparison.

[11]Both exchange rates equal the price of one unit of foreign currency (or a basket of foreign currencies) in units of the domestic currency: an increase indicates a depreciation of the domestic currency.

[12]On January 14, 2021, the BOI changed its strategy by announcing the total amount of USD that it planned to buy in 2021. The BOI was, however, silent about the timing of these USD purchases and did not declare how much USD it planned to buy on any given day. See: `https://www.boi.org.il/en/NewsAndPublications/PressReleases/Pages/14-1-21.aspx`.

on December 31, 2019, a few weeks before the global COVID-19 pandemic erupted.

Figure 1: Foreign value of the ILS and the size of foreign exchange interventions



Notes: The figure displays monthly averages of the nominal effective exchange rate (NEER) and the USD/ILS spot rate (both on the left axis), as well as the monthly total volume of interventions in USD millions (right axis). The NEER and the USD/ILS are both computed as indices and normalised to 100 as of January 2008. Both indices are defined in units of the domestic currency per unit of foreign currency. A decrease in the index level therefore indicates an appreciation of the domestic currency. The data covers the period from January 2008 to December 2019.

Main results. Our main results can be summarized as follows: (1) Using the continuously updated generalized method of moments (GMM) estimator, we find that interventions amounting to USD 1 billion are associated with a 0.85% depreciation of the USD vis-à-vis the ILS and a 0.82% depreciation of the NEER, which is large by both international and historical standards. The initial impact of the USD purchases remains significant up to two (five) trading days for the USD/ILS exchange rate (NEER).[13] (2) We find that a higher USD/ILS risk reversal (RR), reflecting a more pronounced tilt towards a stronger USD over the lifetime of this option strategy,[14] is associated with higher future interventions for all maturities except for the one-month RR. Therefore, the options market seems to price in future interventions. (3) On the contrary, the higher moments (volatility, skewness, and kurtosis) of the RND – proxied by the scaled price quotes of USD/ILS options – do not change as a response to the BOI's interventions, neither contemporaneously nor in the following trading days. This lack of adjustment of the higher moments of the RND, combined with the large effect that the BOI's interventions have on the USD/ILS forward rate, implies that the BOI locationally shifts the whole distribution

[13]Throughout the paper, we assess the effect of intervening by USD 1 billion. However, we stress that the amount is not the average daily intervention.

[14]That is, a positive skewness of the RND, as the RR is frequently positive in the period of interest (undocumented results).

towards higher USD/ILS values without affecting the options market view on the higher-order risks. Crash risk, for instance, is unaffected. The options market seems to price in future interventions (see result (2)), while the price quotes are not adjusted when these interventions are actually carried out. We interpret the adjustment behavior as evidence that the BOI is successful in shaping market expectations in the intended direction. (4) We also examine the effect that interventions have on the USD/ILS forward rates, the first moment of the RND. We find that interventions increase the price of the USD/ILS 3-month forward rate by 0.72%, which is less than the effect on the two spot rates that we consider. The lower effect implies that the intervention activity makes the deviations from covered interest rate parity (CIP) – usually referred to as the cross-currency basis – more negative. This finding is in line with the theoretical predictions of Amador, Bianchi, Bocola, and Perri (2020), who propose a framework to study the problem of a central bank that pursues an exchange rate policy (e.g., to stimulate labor demand) that leads to a violation of interest parity when the zero lower bound binds.

Price discovery in option markets. The question naturally arises as to why the information of an upcoming intervention is priced in the options market but not in the spot market,[15] as both markets are connected by put-call parity, unless there are arbitrage opportunities to exploit.[16] Two potential answers come to mind: (1) **limits to arbitrage.** Papers such as Duffie (2010), Gromb and Vayanos (2010) and Du, Tepper, and Verdelhan (2018) show that balance-sheet constraints may prevent arbitrageurs (e.g. banks) from eliminating arbitrage opportunities. In the case of FX markets, Menkhoff, Sarno, Schmeling, and Schrimpf (2012) argue that limits to arbitrage help explain the profitability of momentum strategies. The argument for constrained arbitrageurs seems particularly relevant in our case, as we find that a one standard deviation increase in the daily change of the RR for all the maturities that we examine is associated with an increase of the expected size of interventions amounting to only USD 4 million (USD). Assuming a USD 1 billion intervention, which is associated with a 0.85% depreciation of the USD/ILS spot rate according to our empirical results, implies that the options market is anticipating a mere mUSD $4 \times 0.85\% = 0.0034\%$ depreciation, which is less than 1% of the standard deviation of the daily USD/ILS returns. Therefore, the costs for arbitrageurs may potentially outweigh their expected profits. (2) **Derivative's market sophistication**. Market participants in the derivatives market may be more sophisti-

[15]The fact that the USD/ILS options market does not significantly adjust its prices when interventions are carried out, while the USD/ILS spot rate significantly changes suggests that the impact of future intervention episodes on the future spot exchange rate is priced in the former case.

[16]See, for instance, Cox and Hobson (2005) and Heston, Loewenstein, and Willard (2007) who demonstrate that this parity breaks down when the martingale property is lost for a financial security.

cated than in the spot market. Empirically, price discovery analyses indeed suggest that FX derivative markets lead spot FX markets in pricing in news, see Tse, Xiang, and Fung (2006) and Rosenberg and Traub (2009).

Related literature and our contributions. We contribute to the strand of literature on FX interventions in at least three dimensions. First, there are only few studies that analyze how FX interventions affect market expectations about the future foreign value of a currency and its risk characteristics as reflected in the options market (i.e. captured by the option-implied volatility (IV), skewness, and kurtosis of the RND).[17] The results of these papers are rather mixed; they usually do not find a statistically significant relation between interventions and the price quotes of these option contracts (or the higher-order risk-neutral moments extracted from these options). Contrary to these papers, however, we do not limit ourselves to analyzing options with a specific maturity, but explore options with maturities ranging from one to twelve months. This part of our empirical analysis is relevant for monetary policymakers, as they can learn about the persistence of the effect that spot FX market interventions have on FX options.

The second strand of literature that we contribute to is the literature that estimates the effect that FX interventions have on the spot FX market.[18] In a recent contribution, Adler et al. (2019), analyzing a panel of 52 countries (13 developed (including Israel) and 39 emerging market countries) from 1996 to 2013, find that purchases of foreign currency amounting to 1% of GDP cause a depreciation of the nominal exchange rate in the range of 1.7% to 2.0%. A recent meta-analysis by Arango-Lozano et al. (2020) covers 74 empirical studies that have analyzed FX interventions in 19 countries across five decades, including both emerging and industrialized countries. They find that a net purchase of USD 1 billion is associated with a depreciation of the domestic currency by 1%. The authors emphasize, however, that they find evidence of a weak positive publication bias. Their estimate is therefore modestly upward biased. How do these findings compare with our results? Our estimated coefficient, re-scaled such that it reflects a volume of USD purchases amounting to 1 percent of Israeli GDP, is approximately equal to 2.7% (NEER: 2.6%).[19] The BOI's impact is consequently larger than the upper bound of other relevant studies. A shortcoming of this strand of literature is the fact that most of the

[17] See, for instance, Castrén (2004), Fratzscher (2005), Galati et al. (2005), Galati et al. (2007), Disyatat and Galati (2007), Morel and Teïletche (2008), Marins, Araujo, and Vicente (2017).

[18] See, for instance, Sarno and Taylor (2001), Neely (2005), Fratzscher (2005), Égert and Komárek (2006), Disyatat and Galati (2007), Fatum (2015), Ribon (2017), Caspi et al. (2018), Adler, Lisack, and Mano (2019), Nedeljkovic and Saborowski (2019)) and Arango-Lozano et al. (2020).

[19] To get the volume of USD purchases amounting to 1% of domestic GDP, we calculate the average of the annual nominal GDP of Israel in the period 2013-2019 (denominated in USD) and multiply this average by 1%. We divide the resulting 1% of GDP estimate by USD 1 billion. The resulting factor of 3.2 is multiplied by our estimated coefficients.

existing contributions cover the years before the GFC. Given the historically exceptional period of sustained low interest rates in the aftermath of the GFC and the changes that the FX market has undergone in the last decade in response to technological innovations and the endorsement of a set of voluntary standards within the "Global Code of Conduct" regulatory framework,[20] it is important to have more recent empirical analyses on this topic, as the results documented in older studies may no longer be representative for how interventions affect spot FX markets.

The third strand of literature that we contribute to is the recently revived literature attempting to explain deviations from CIP (i.e., a non-zero cross-currency basis).[21] It can be shown that these CIP deviations are a direct proxy for the costs of FX interventions (Amador et al., 2020). To the best of our knowledge, our paper is the first to empirically quantify the effect that FX interventions have on the cross-currency basis. We find that FX interventions widen this metric, as predicted by the Amador et al. (2020) model.[22] Note that previous academic contributions have erroneously used deviations from uncovered interest parity to proxy for the costs of FX interventions instead (Amador et al., 2020), which reinforces our view that our work is the first academic contribution that directly links FX interventions to the dynamics of the cross-currency basis.

This paper is structured as follows. In Section 2 we describe our methodology, our estimation strategy and the data that we use. Section 3 presents and discusses our main results, while Section 4 presents our conclusions.

2 Methodology, estimation strategy and data

2.1 Generalized Method of Moments

To assess the impact that the BOI's FX interventions have on the foreign value of the ILS and on the USD/ILS options market, we first run simple OLS regressions. We ignore potential endogeneity biases for now caused, for instance, by the hard to disentangle simultaneity of FX interventions and spot FX rate movements that trigger these interventions (hint: "leaning against the wind").[23] Notice, however, that using daily data significantly

[20]See, for example, McGeever (2017) and Szalay (2020) for details about the global FX rigging scandal that initiated the reforms that have led to the creation of voluntary standards.

[21]See Du et al. (2018), Avdjiev, Du, Koch, and Shin (2019) and Du and Schreger (2021), among others.

[22]In their empirical exercise, Amador et al. (2020) assess the relationship between deviations from CIP and monthly foreign reserves as a proxy for the actual size of interventions. Foreign reserves, however, are only a crude proxy for the latter (Neely, 2000), especially if used on a monthly basis, where macroeconomic factors and news affect the domestic value and the size of these reserves, which may bias their empirical results.

[23]See Section 2 in Neely (2005), subsection 3.2 in Fratzscher (2005) and Section 3 in Tashu (2014) for details.

reduces the risk that reverse causality and confounding factors may bias our estimated coefficients (Menkhoff, Rieth, and Stöhr, 2021). In addition, this exercise allows us to get a feeling about how sizable these biases are.

In a second step, we run GMM regressions – allowing us to control for endogeneity[24] – and include additional controls to shield against omitted variables bias. The GMM procedure has four additional advantages. First, this procedure requires no distributional assumptions. Second, many econometric models can be estimated with this procedure, as they often are simply special cases of the GMM procedure (Cochrane, 2005). Third and fourth, the GMM procedure is also general in the sense that it allows for heteroskedasticity of unknown form and that it can be used when serial correlation cannot be precluded ex ante. In this case, the effect on the estimated standard errors can be accounted for by using a heteroskedasticity and autocorrelation (HAC) consistent covariance matrix.

Expressing the model of interest as:[25]

$$\mathrm{E}\left[f(w_t, z_t, \theta)\right] = 0, \tag{1}$$

where f represents a vector of R population moment conditions, w_t denotes a vector of observable (endogenous or exogenous) variables, z_t is a vector of predetermined instruments and θ a vector containing the K unknown parameters that we are interested in.

Replace the expectation in Equation (1) with its sample counterpart to get an expression that allows us to estimate the entries of the parameter vector θ:

$$g_T(\hat{\theta}) \equiv \frac{1}{T}\sum_{t=1}^{T} f(w_t, z_t, \hat{\theta}), \tag{2}$$

with T and $g_T(\cdot)$ equal to the number of periods and the sample means of the deviation of the R sample moment conditions from their population counterparts, respectively.

When we have less sample moment conditions than unknown parameters (i.e. $R < K$), the parameter vector $\hat{\theta}$ is unidentified. When the number of sample moment conditions equals the number of unknown parameters (i.e. $R = K$), we have a system of $R = K$ moment conditions with K unknowns. Hence, the parameter vector $\hat{\theta}$ can be exactly identified by simply setting the $R = K$ elements in Equation (2) equal to zero. Finally, when the number of moment conditions exceeds the number of parameters (i.e. $R > K$), the GMM estimator $\hat{\theta}_{GMM}$ is chosen such that it minimizes a quadratic form of $g_T(\hat{\theta}_{GMM})$

[24] The empirical literature mainly uses either GMM regressions or instrumental variable-panel approaches to shield against potential biases due to simultaneity (see e.g. Adler and Tovar (2011) and Adler et al. (2019)).

[25] The following exposition follows Chapter 11 in Cochrane (2005) and Chapters 1 and 3 in Hall (2005).

in combination with a symmetric, positive definite weighting matrix W_T:

$$\underset{\hat{\theta}_{GMM}}{\operatorname{argmin}}\, Q_T(\hat{\theta}_{GMM}) = \underset{\hat{\theta}_{GMM}}{\operatorname{argmin}}\, g_T(\hat{\theta}_{GMM})' W_T g_T(\hat{\theta}_{GMM}). \tag{3}$$

It can be shown that the asymptotically efficient GMM estimator of this quadratic form is asymptotically normally distributed:

$$\sqrt{T}\left(\hat{\theta}_{GMM} - \theta\right) \xrightarrow{a} \mathcal{N}(0, V), \tag{4}$$

with V representing the asymptotic covariance matrix.

Continuously updated GMM estimator. Notice that the estimated parameters depend on the weighting matrix W_T. Hansen, Heaton, and Yaron (1996) have proposed a GMM estimator that in small samples often exhibits better properties compared to the two-step (or iterated) GMM estimator. The proposed estimator is known as the continuously updated GMM estimator (CU-GMM), as it uses a covariance matrix W_T that is updated in each step of the GMM algorithm until it converges. To assess the robustness of our results, we use this GMM estimator in the empirical section in addition to simple OLS regressions.

2.2 Data

2.2.1 Foreign exchange interventions data

Table 1 includes selected descriptive statistics of the monthly average of the FXI data from the BOI for the period from January 2013 to December 2019 analyzed in the empirical section. The descriptive statistics indicate that, on average, the BOI purchased mUSD 594 per month, with a minimum of mUSD 2 and a maximum of USD 2.27 billion. The monthly intervention volumes are relatively volatile, as reflected in the standard deviation. In total, we have 69 out of 84 months with at least one trading day, where the BOI intervened in the USD/ILS spot market. The table also suggests that the distribution of the FXI data might be right-skewed, as the mean is larger than the median. In other words, the distribution seems to exhibit a long tail in the positive direction of the number line. In essence, there are a few observations that are large compared to all other FX intervention data, which is confirmed in an untabulated histogram of the monthly FX intervention data.

To give a better sense of the magnitude of FX interventions relative to some other metrics and in terms of calendar time, Table 2 includes information about the average size of FX interventions relative to Israeli GDP and the daily USD/ILS spot market

Table 1: Descriptive statistics of the monthly foreign exchange interventions data

	Mean	Median	Std	Min	Max	N
FXI	0.594	0.350	0.545	0.002	2.266	69

Notes: The table shows descriptive statistics of the monthly intervention data in USD billions (columns 2–6) and the total number of months in the period of interest with at least one intervention day (column 7). The data covers the period from January 2013 to December 2019.

turnover (confidential data from the BOI), as well as the average length of the different FX intervention episodes:

Table 2: Descriptive statistics of the daily foreign exchange interventions data

Indicator	Total
Average daily intervention size as share of GDP (%)	0.05
Average daily intervention size as share of daily traded FX volume (%)	8.16
Average length of episode in seven days	1.46
Average length of an episode in a trading week (in days)	1.73

Notes: The table displays the descriptive statistics of the daily intervention data. The GDP series is in US dollars and is compiled by the Israeli Central Bureau of Statistics (row 1). The daily traded volume in the USD/ILS market is compiled by the BOI (row 2). Row 3 displays the average length of an intervention episode within any given week (i.e. from Monday to Monday, from Tuesday to Tuesday, etc.). The average length of an episode in a trading week (row 4) shows the average number of consecutive days of daily interventions in a calendar week. The data covers the period from January 1, 2013 to December 31, 2019.

From this table we learn that the size of the BOI's FX interventions is large in terms of domestic GDP. Fratzscher, Gloede, Menkhoff, Sarno, and Stöhr (2019), for instance, document that the size of FX interventions by countries with a free-floating regime amounts to only 0.02% of GDP on average, which is around 60% smaller. Also, relative to the average daily turnover in the USD/ILS spot and forward market, the size of the BOI's FXI is large. Fatum (2015) who analyzes the Bank of Japan's (BOJ) FX intervention activity reports an average size of USD purchases amounting to only 1.3% of the daily market turnover, compared to 8.16% in the case of the BOI. Compared to other central banks' FX intervention episodes, this evidence suggests that FX market participants may partially be able to infer when the BOI is intervening, as the FX intervention volume is relatively large by international standards. This will later become relevant when interpreting our empirical results.

We also see that the BOI participates in the USD/ILS spot market for only 1.46 trading days on average, which is rather short by international standards. Disyatat and Galati (2007), for instance, report that the Czech National Banks's (CNB) FX intervention activity spanned a period of eight trading days on average. The BOI, nevertheless, seems to intervene on more than one trading day in a given trading week (for instance, at the beginning and at the end of a trading week). As explained in Miyajima (2013), FX interventions which are also aimed at affecting market expectations should combine intervention episodes with days of no activity to allow FX derivatives market participants to evaluate the effect of these interventions over longer horizons – the BOI apparently follows this advice.

2.2.2 Exchange rates, transaction volumes and financial variables

Table 3 provides selected descriptive statistics of the main variables that we use in the empirical section of our paper. These variables are recorded on a daily basis and span the period from January 1, 2013 to December 31, 2019. In total, the data contain a maximum of 1826 trading days.[26]

The upper panel of the table ("Exchange rates") shows the daily exchange rate returns (in percent and in logs) of the USD/ILS and the EUR/USD FX rate, the NEER, and the 3-month USD/ILS forward rate. The statistics indicate that the ILS appreciated vis-à-vis the USD and the currencies of its major trading partners by 0.004% and 0.014% on average, which is in line with the time series in Figure 1. The displayed time series suggest – all else being equal – that the ILS appreciated more vis-à-vis the currencies of Israel's major trading partners ex USA, than against the USD itself. Similarly, the USD on average appreciated against the EUR by 0.009% per trading day.

Focusing on the USD/ILS FX market, the second upper panel of the table ("USD/ILS transaction volume") provides information on the daily FX market transaction volume in mUSD. The data indicate that the volume of over-the-counter (OTC) traded USD/ILS options exhibits a market share of approximately 6.4% on average.[27] Although this number may seem small at first sight, it is large when compared to the corresponding metric in other countries (see the discussion in the next Section 2.2.3).

Daily net flows in the third upper panel of this table ("Flows") are inflows minus outflows of daily ILS spot market purchases in mUSD.[28] They are subdivided into foreign flows (that is, flows by non-residents, such as foreign institutions and foreign retailers) and local flows (that is, flows by residents) by the real sector (for instance, imports and exports of manufactured goods) the financial sector and institutional investors. The data reveal that foreign investors have on average purchased ILS amounting to mUSD 24.7

[26]There are some missing observations in the volume data and also to a much lesser extent in the flows data (i.e. on six trading days). In these cases, we linearly interpolate the data.

[27]Measured as the average total transaction volume of OTC USD/ILS options (i.e. mUSD 395.39) divided by the average total USD/ILS transaction volume (i.e. USD 6.17 billion).

[28]The inclusion of the flow variables in our regressions is motivated by the work of Fanelli and Straub (2021), where capital flows play a crucial role in triggering FX interventions.

per day. On a net basis, mUSD 18.7 ILS have been purchased by residents, mainly by residents from the real sector. This sector has therefore been responsible for the major increase in Israel's current account balance in the period under review.

Table 3: Descriptive statistics of the main variables

	Mean	Median	Std	Min	Max	AR(1)	N
Exchange rates (in logs and in %):							
ΔUSD/ILS	−0.004	0.00	0.38	−2.32	2.41	−0.01	1826
ΔEUR/USD	−0.009	0.01	0.47	−2.30	2.95	0.01	1826
ΔNEER	−0.014	−0.02	0.32	−2.02	2.34	0.02	1826
ΔForward_$3m$	−0.005	−0.02	0.37	−2.29	1.59	0.05	1826
USD/ILS transaction volume (in mUSD):							
Spot and forward	1660.34	1643.89	875.37	0.04	6399.10	0.10	1769
Swap	4109.50	4118.74	1853.63	0.00	11623.51	0.18	1749
OTC options	395.39	277.84	419.14	0.00	5354.98	0.23	1744
Net flows (in mUSD):							
Foreign flows – total	−24.74	−14.51	157.26	−646.42	736.51	0.36	1820
Local flows – real sector	17.13	10.97	113.66	−552.53	547.44	0.26	1820
Local flows – financial sector	5.60	4.79	80.30	−691.88	578.90	0.03	1820
Local flows – inst. investors	−4.06	0.00	86.26	−563.37	734.31	0.23	1820
Misc (in %):							
5-year Israeli CDS	0.80	0.74	0.20	0.48	1.52	0.9952	1826
TELBOR	0.38	0.10	0.47	0.10	1.75	0.9995	1826
USD LIBOR	0.82	0.41	0.82	0.08	2.40	0.9997	1826
VIX	14.86	13.89	3.81	9.14	40.74	0.9281	1763

Notes: The table presents descriptive statistics of the main variables. The data is recorded on a daily basis and spans the period from January 1, 2013 to December 31, 2019. There are a maximum of 1826 trading days. The FX rates are expressed in log changes and in percent. Both FX rates (USD/ILS and EUR/USD), the 5-year Israeli CDS spread and the one-month USD LIBOR are retrieved from Bloomberg. The NEER series is constructed such that it is synchronized with the USD/ILS trading time (see online Appendix B for more information). Forward_3m is the three-month USD/ILS forward rate retrieved from Bloomberg. The daily transaction volume in the USD/ILS spot, forward, swap and OTC options market are compiled by the BOI and denominated in millions of USD ("mUSD"). Daily net flows are computed as inflows minus outflows of USD in exchange for ILS in mUSD. The flows are sub-divided into foreign flows, which are net flows by non-residents (foreign institutions, retailers, etc.) and local net flows by the real sector (i.e. importers and exporters), the financial sector and institutional investors. TELBOR is the one-month Israeli interbank rate published by the BOI. We linearly interpolate missing TELBOR rates (due to Israeli holidays). VIX measures the implied volatility from S&P 500 index options at US closing time and is provided by the CBOE. It has less trading days than the other variables due to US holidays.

The table also displays descriptive statistics in the lower panel ("Misc") for the 5-year Israeli CDS spread. On average, the CDS spread equaled 80 basis points (bps) in the period of interest, which is low by international standards and in line with Israel's high (investment grade) credit rating.[29] The table also shows that the one-month USD LIBOR has been larger on average than the one-month TELBOR (0.82% vs. 0.38%). Hence, by CIP, the USD should depreciate vis-à-vis the ILS on average, thereby putting appreciation

[29] Israel's credit rating was last set at A1 by Moody's with a stable outlook on April 24, 2020 (as of the date of writing the paper). This credit rating has remained unchanged since May 6, 2006.

pressure on the ILS. The last row displays the descriptive statistics for the VIX as a proxy measure of global uncertainty.

2.2.3 The USD/ILS options market

In this subsection, we concentrate on the USD/ILS options data that we use in the empirical section. The data is retrieved from Bloomberg. Table 4 displays selected descriptive statistics of the main USD/ILS option trading strategies. The data is recorded on a daily basis and spans the period from January 1, 2013, to December 31, 2019. The data include 10-Δ and 25-Δ[30] RRs (upper panel), 10-Δ and 25-Δ butterfly (BF) spreads[31] (middle panel) and at-the-money implied volatilities (ATMV)[32] (lower panel) for six maturities, ranging from one week ("1w") to twelve months ("12m").[33] The price quotes are measured in implied volatilities and displayed in percent, following the options markets' quoting convention.[34]

Notice that the price quotes of these option strategies are highly persistent (column "AR(1)"). Therefore, we use them in first differences throughout our analysis. Untabulated results show that the first difference eliminates the high persistence in these price quotes. We also note that only the price quotes of the one-week BF spreads for both option deltas exhibit lower persistence compared to the other price quotes. This is also true, but to a much lesser extent, for the one-week RRs (also for both option deltas) and the one-week ATMV.[35] The lower persistence of these five price quotes might indicate stale prices and a lack of liquidity, which brings us to our next topic.

As we use options data extensively in our paper, we assess how liquid the Israeli FX option market is by international standards. To this end, we look at the most recent data from the BIS triennial central bank survey that covers 54 countries and includes collected data from close to 1300 banks and other dealers on FX turnover, amongst others. The

[30]For instance, a 10-Δ call (put) corresponds to a Garman and Kohlhagen (1983) option delta of 0.1 (-0.1), as FX options are quoted in terms of the GK model by market convention.

[31]See online Appendix C for details on risk reversals and butterfly spreads.

[32]The ATMV isn't an option strategy, but we call it a strategy to be consistent with the RRs and the BF spreads.

[33]Online Appendix D displays the coefficients of the cross-correlation between the log returns of these three option strategies (Tables C.2, C.3 and C.4). The cross-correlations indicate that the three strategies are highly correlated with each other, and even more so for strategies with the same option delta. We also include in these three tables the correlation between the log returns of these option strategies and the daily change of the USD/ILS exchange rate. The results show that the former is positively correlated with the RRs, reflecting a kind of momentum. This contemporaneous relationship between RRs and spot FX rates was first documented in McCauley and Melick (1996), Malz (1997) and Campa, Chang, and Reider (1998) and implies that investors assign a more pronounced (risk-neutral) tilt towards a further depreciation of the ILS vis-à-vis the USD (i.e. a higher RR), when the ILS has already weakened (i.e. a higher USD/ILS exchange rate).

[34]For details, see Reiswich and Wystup (2010).

[35]That is, the price quotes of the USD/ILS option strategies with the shortest maturities.

Table 4: Descriptive statistics of three USD/ILS option strategies

	Mean	Median	Std	Min	Max	AR(1)	N
Risk reversals:							
10-Δ:							
RR101w	0.658	0.60	0.43	-0.42	2.77	0.95	1826
RR101m	1.088	0.93	0.67	-0.12	3.33	0.99	1826
RR103m	1.438	1.14	0.87	-0.05	3.58	0.997	1826
RR106m	1.649	1.31	0.98	0.00	3.76	0.998	1826
RR109m	1.750	1.41	1.05	0.16	4.12	0.998	1826
RR1012m	1.950	1.67	1.09	0.26	4.30	0.998	1826
25-Δ							
RR251w	0.396	0.37	0.26	-0.12	1.49	0.976	1826
RR251m	0.597	0.5	0.37	-0.07	1.83	0.994	1826
RR253m	0.782	0.61	0.47	-0.02	1.92	0.998	1826
RR256m	0.892	0.70	0.53	0.01	1.99	0.998	1826
RR259m	0.949	0.78	0.57	0.10	2.13	0.999	1826
RR2512m	1.045	0.88	0.58	0.18	2.24	0.999	1826
Butterfly spreads:							
10-Δ:							
BF101w	0.794	0.90	0.44	-1.67	1.92	0.429	1826
BF101m	0.738	0.73	0.12	0.46	1.12	0.918	1826
BF103m	1.008	0.98	0.21	0.59	1.45	0.976	1826
BF106m	1.186	1.14	0.25	0.65	1.73	0.982	1826
BF109m	1.269	1.19	0.29	0.69	1.92	0.983	1826
BF1012m	1.452	1.41	0.32	0.78	2.20	0.985	1826
25-Δ:							
BF251w	0.136	0.20	0.30	-2.45	1.20	-0.052	1826
BF251m	0.236	0.23	0.04	0.14	0.37	0.945	1826
BF253m	0.327	0.31	0.07	0.19	0.50	0.984	1826
BF256m	0.384	0.37	0.08	0.21	0.59	0.986	1826
BF259m	0.419	0.39	0.10	0.22	0.63	0.990	1826
BF2512m	0.474	0.46	0.11	0.25	0.71	0.990	1826
At-the-money implied volatilities:							
ATMV1w	6.63	6.35	1.49	3.54	11.43	0.947	1826
ATMV1m	6.56	6.35	1.29	3.96	10.33	0.994	1826
ATMV3m	6.64	6.47	1.14	4.29	9.72	0.997	1826
ATMV6m	6.73	6.54	1.05	4.76	9.41	0.998	1826
ATMV9m	6.81	6.61	1.00	5.07	9.21	0.999	1826
ATMV12m	6.86	6.67	0.96	5.18	9.05	0.999	1826

Notes: The table displays descriptive statistics for the daily USD/ILS option strategies quoted in implied volatilities and in percent (except columns "AR(1)" and "N") for the period from January 1, 2013 to December 31, 2019, a total of 1826 trading days. The data includes 10-delta and 25-delta risk reversals ("RR10" and "RR25"), 10-delta and 25-delta butterfly spreads ("BF10" and "BF25") and at-the-money implied volatilities ("ATMV"). In each case the data is available for six different maturities, ranging from one week ("1w") to twelve months ("12m"). Data source: Bloomberg.

survey begins in April 2007.[36] Our calculations (see Table E.1 in online Appendix E) reveal that the ratio of OTC-traded FX option volume to the total FX transaction volume[37] in Israel equaled 6.2% in 2019, which is large by international standards. Indeed, Israel is

[36]Source: https://www.bis.org/statistics/rpfx19.htm.

[37]Including transactions in the FX spot, FX forward, FX option and FX swap market.

consistently ranked in the top five of all surveyed countries in terms of the ratio of total FX options transaction volume to total FX transaction volume since April 2007 (untabulated results).

The results in Tables E.2-E.4 in online Appendix E add further support to our argument. The figures show the box plots of the bid-ask spreads (BAS) divided by the mid-quote of the three USD/ILS option strategies that we use in our paper for 28 currency pairs across six maturities.[38] We note two things: (1) The relative BAS is generally higher for the one-week contracts. We will therefore omit these contracts in our analysis. (2) The results show that the relative BAS for the three option strategies are consistently ranked in the interquartile range, which makes us confident that our option market data is not significantly affected by low liquidity. This finding indicates that valuable information can be extracted from the price quotes of USD/ILS options.

3 Results

As described in Section 1, the empirical evidence to date indicates that FX interventions significantly affect the targeted FX spot rate in the desired direction. We hypothesize that FX interventions may also affect the market's perception of the uncertainty associated with the future FX spot rate, as reflected in the FX options market. Before we assess to what extent FX interventions in the USD/ILS spot market affect price quotes (and the herewith associated option-implied higher moments of the extracted RND) in the options market, we first confirm that FX interventions indeed depreciate the the foreign value of the ILS in the period under review.

3.1 Effect of interventions on the foreign value of the ILS

3.1.1 Informal event study

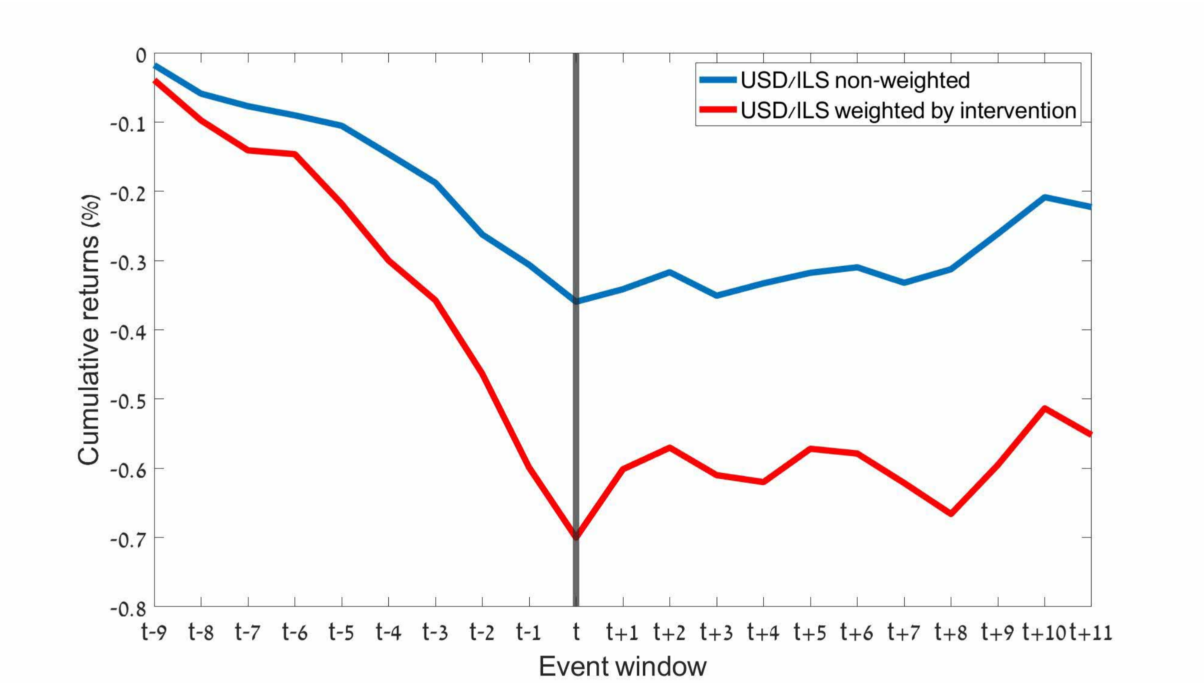
We begin with an informal event study by displaying, in Figure 2, the average cumulative returns of the USD/ILS spot rate (Panel (a)), the NEER (Panel (b)), and the three-month USD/ILS forward rate (Panel (c)), starting 9 days prior to an intervention episode (starting at the beginning of day t) and ending 11 days after the first intervention day. The average cumulative returns are weighted using the relative size of interventions,[39] as

[38] As the implied volatility levels vary across currencies, we scale the BAS to make this metric comparable across currency pairs (e.g., to assess the liquidity of a specific FX rate compared to other currency pairs).

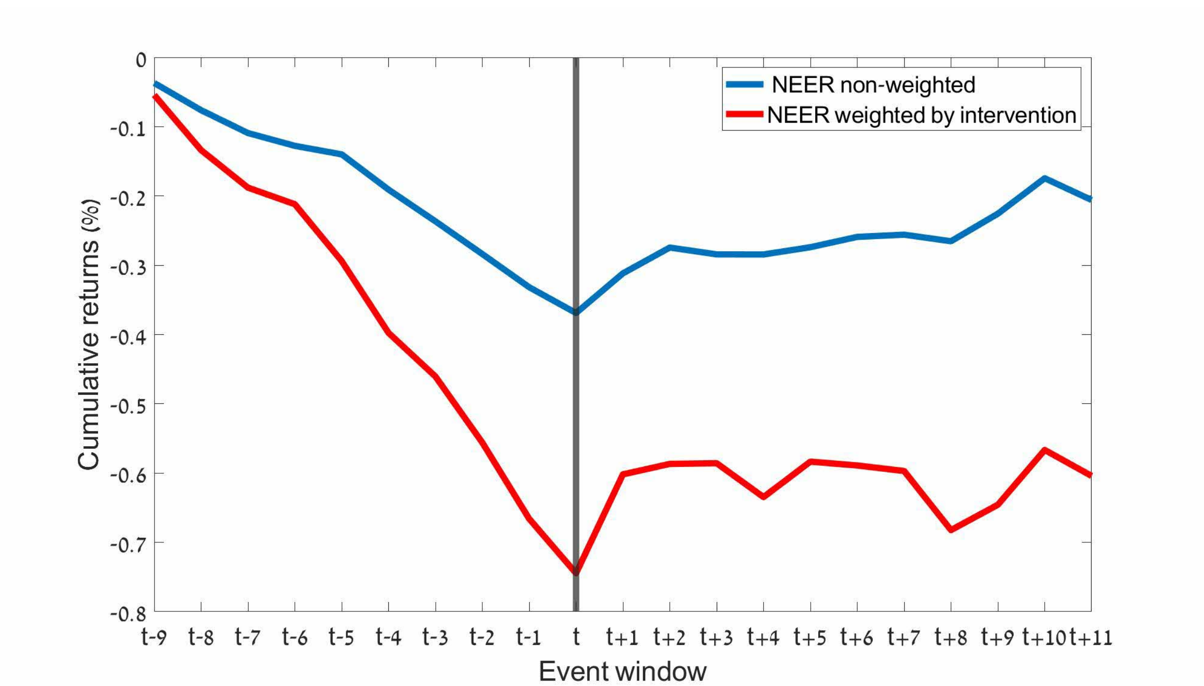
[39] The size of FX interventions at a specific day $t + j$ (with $j \in \{-9, -8 \ldots, 0, \ldots, +10, +11\}$) divided by the total size of FX interventions in our sample period.

Figure 2: Cumulative returns of the USD/ILS spot FX rate, the NEER and the 3-month USD/ILS forward rate around the intervention episodes

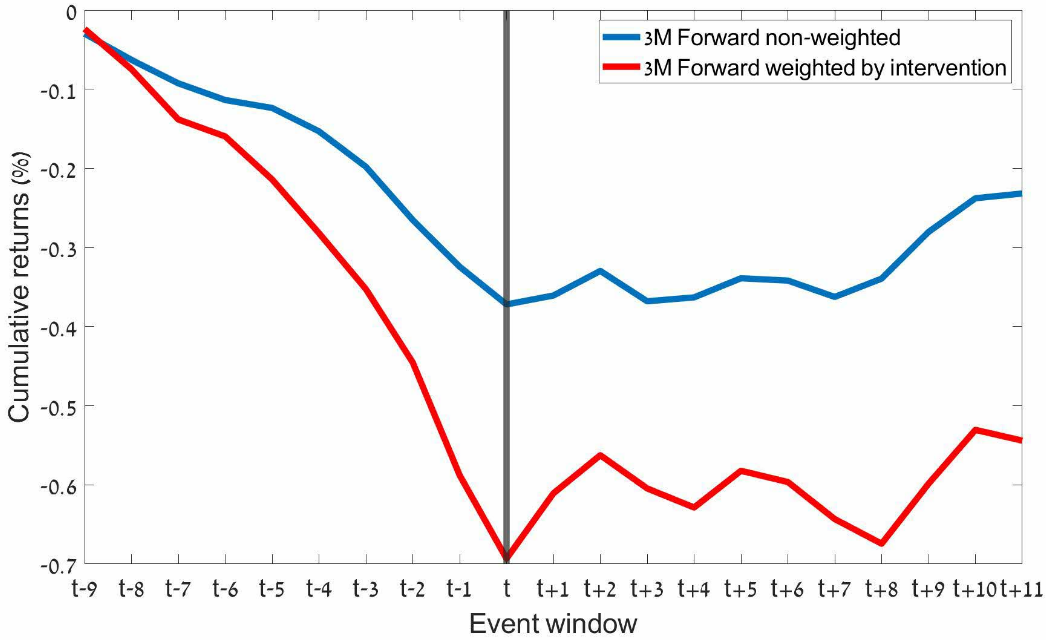
(a) Cumulative returns of the USD/ILS spot FX rate.



(b) Cumulative returns of the NEER.



(c) Cumulative returns of the 3-month USD/ILS forward rate.



Notes: The figure shows the average cumulative returns of the USD/ILS exchange rate and the NEER (both in percent), and the three-month USD/ILS forward at time $t-9$ to $t+11$ on a daily basis, where t reflects the beginning of the trading day when the first intervention was carried out. The red line displays the cumulative returns weighted by the relative size of interventions, while the blue line shows this metric using equal weights for each intervention episode.

we have learned from Table 1 (and the herewith associated following discussion) that the distribution of FX interventions is right-skewed. For ease of comparison, we also display the cumulative returns assigning equal weights to each FX intervention episode, irrespective of the actual size of USD purchases. Equally weighting the FX intervention episodes tilts the results in favour of those episodes where the size of FX interventions was relatively small.[40]

We see that the BOI's FX interventions contain the appreciation trend of the foreign value of the ILS (both in the FX spot and the FX forward market) and create a depreciation of the ILS by the end of the first FX intervention day. There is also a slight continuation of this "trend reversal" on day $t+1$,[41] which may reflect a second intervention day in some cases. The figures also show that weighting the returns by the intervention volumes results in more pronounced appreciation and depreciation trends prior to and after day t, respectively. The result implies that the BOI seems to intervene more heavily when there is a more pronounced (or steeper) appreciation trend prior to the first intervention day t. All in all, these figures imply that the bank is successful in creating a lasting depreciation in the USD/ILS FX market according to the success "event" and

[40] As a by-product, this also allows us to learn about the reaction function of the BOI.

[41] That is, the ILS continues to depreciate on the first trading day after the first intervention day.

"direction" criterion in the FX intervention strand of literature.[42] In the next sections, we examine the effect of the BOI's intervention activity more rigorously, while controlling for the inherent endogeneity and other factors.

3.1.2 Econometric assessment of the contemporaneous effect

As previous research has shown, estimating the causal effect of FX interventions on the FX spot rate using OLS results in downward-biased estimates. The bias arises because of the endogeneity caused by the "stylized fact" that central banks typically intervene to respond to adverse spot rate movements, thereby "leaning against the wind".

First-stage regression. To circumvent the endogeneity, we follow the standard approach in the literature and adopt instruments in the GMM framework that are correlated with the intervention data but not with the shocks that affect the FX rate on the days when the BOI intervenes.[43] Specifically, we use instruments that are commonly used in the FX literature and are defined in online Appendix B. Our instruments include the one-day lagged daily intervention volume, a dummy variable that equals one if there has been an intervention in the previous calendar week, the one-day lagged three-month return of the USD/ILS spot rate, the one-day lagged two-day return of the NEER, the three-day lagged two-week return of the NEER, the one-day lagged one-month change in the 5-year Israeli CDS spread, and the one-day lagged two-week change in the US VIX to proxy for changes in global uncertainty. As controls, we use contemporaneous explanatory variables. Specifically, we use the one-day change of the EUR/USD spot rate, the one-week change in the VIX and the one-week change of the one-month USD LIBOR. We chose the lags of the instruments based on adjusted R^2 criteria (i.e., selecting the specifications with the highest $\bar{R}^2$).

The result of the first-stage regression are displayed in Table 5. We see that most estimated coefficients have the expected sign, pointing to a "leaning against the wind" intervention activity. Our results are in line with the results in Ribon (2017), although her results are for monthly data.

Because we use all the instruments of this first-stage regression specification as instruments for our CU-GMM estimation, we also include the Kleibergen and Paap (2006) Wald F-statistic. The test statistic significantly exceeds the Stock and Yogo (2005) critical value. We can therefore reject the null hypothesis that the instruments have insufficient explanatory power (that is, our instruments pass the weak identification test) – the test

[42]See Humpage (1999), Fatum and Hutchison (2003), Fratzscher (2005), Fatum and Hutchison (2006), Galati et al. (2007), Fatum (2008), Fratzscher (2008) and Fratzscher et al. (2019).

[43]One can also take a different approach to identifying the causal effect of interventions on the FX spot rate by using intra-day intervention data, see for example Caspi et al. (2018).

Table 5: First-stage regression

	Dependent variable: FXI_t (in USD billion)
Controls	
Intercept	0.012***
	(5.90)
$\Delta\text{EUR/USD}_{t-1,t}$	0.010***
	(2.39)
$\Delta\text{VIX}_{t-5,t}$	0.0001
	(0.18)
$\Delta\text{LIBOR}_{t-5,t}$	0.146*
	(1.65)
Instruments	
FXI_{t-1}	0.1781***
	(3.94)
$\mathbb{1}_{\{\text{FXI}_{t-6,t-1}>0\}}$	0.0095**
	(2.26)
$\Delta\text{USD/ILS}_{t-61,t-1}$	−0.0018***
	(−3.04)
$\Delta\text{NEER}_{t-3,t-1}$	−0.0148***
	(−3.63)
$\Delta\text{NEER}_{t-13,t-3}$	−0.0031*
	(−1.69)
$\Delta\text{CDS}_{t-21,t-1}$	−0.0004
	(−1.55)
$\Delta\text{VIX}_{t-12,t-1}$	0.0004
	(0.74)
Adjusted R^2	7.24
Kleinbergen and Paap rk Wald F	7.91

Notes: The dependent variable is the size of interventions ("FXI_t") in USD billions, which we obtained from the BOI and is available on a daily basis from January 1, 2013 to December 31, 2019. Summary statistics for the explanatory variables are reported in Tables 3 and 4. The CDS spread is expressed in basis points, the VIX in percent. Detailed information on the other controls and instruments can be found in online Appendix B. To assess whether the instruments in the GMM have sufficient explanatory power, the Kleibergen and Paap (2006) test statistic is included. The Stock and Yogo (2005) critical value for the weak instrument test with 10% maximal LIML size is equal to 3.5. The t-statistics (in parentheses below the coefficients) are the Newey-West HAC corrected t-statistics. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

results suggest that the endogenous regressors are not weakly correlated with the instrument. In other words, we can be confident that we will be able to handily address the endogeneity when using the CU-GMM estimator. The result is important, as this estimator may exhibit poorly-defined finite sample moments when using weak instruments.[44] In addition, with weak instruments, we would have needed more informative instruments

[44] See Hahn, Hausman, and Kuersteiner (2004) and also Donald and Newey (2000), after noticing that the CU-GMM estimator can be interpreted as a jackknife estimator.

or we would have been forced to use an estimator that is less susceptible to biases due to endogeneity.

In Appendix A, we compare the estimated coefficients and the statistical significance across several first-stage regression specifications.[45] From that "sensitivity analysis" we learn that the estimated coefficients are both qualitatively and quantitatively similar. We therefore feel confident about our first-stage regression specification. The adjusted coefficient of determination $\bar{R}^2$ is nevertheless lower than in previous studies that have estimated comparable first-stage regressions.[46] Note, however, that our purpose is not to estimate the BOI's actual reaction function. Our first-stage regression is just a means to effectively control for the inherent endogeneity of FX interventions when running the CU-GMM algorithm, thereby allowing us to get an unbiased estimate of the effect of FX interventions on the FX spot rate. Consequently, the low $\bar{R}^2$ is a minor issue.

Contemporaneous effect. Table 6 displays the results of regressing the daily log return (in percent) of the USD/ILS exchange rate (Panel A), the NEER (Panel B) and the three-month USD/ILS forward rate[47] (Panel C) on an intercept, the intervention variable (in billions of USD), the daily log return of the EUR/USD spot rate (in percent), the one-week change in the VIX (in percentage points) and the one-week change of the USD LIBOR (in percentage points). Column 2 presents the results when running a standard OLS regression, while column 3 displays the results when using the CU-GMM estimator. As a robustness check, we also report the results of a two-stage least squares (2SLS) estimation in the fourth column. The control variables and instruments are the same as in Table 5.

We see that the estimated coefficient associated with the intervention variable is highly statistically significant in all regressions, even when ignoring the potential bias caused by simultaneity and simply using standard OLS - consistent with the fact that using daily intervention data reduces potential endogeneity concerns (Menkhoff et al., 2021). Using the CU-GMM estimator, the estimated coefficients are statistically significant and comparable in size for the two spot rates, equaling 0.85% for the USD/ILS rate (panel A) and 0.82% for the NEER (panel B). The empirical finding is in line with the broad appreciation trends of the ILS vis-à-vis the USD and vis-à-vis the exchange rates that constitute the NEER, which is comparable in both cases, as evidenced in Figure 1.

[45] Also including additional instruments.

[46] See Table 2 in Galati et al. (2005) who obtain an $\bar{R}^2$ of 0.1 and 0.09 for the case of the BOJ and the Federal Reserve, respectively; Table 2 in Disyatat and Galati (2007) with an $\bar{R}^2$ of 0.18 for the CNB; Tables 6 and 9 in Galati et al. (2007) who report an $\bar{R}^2$ of 0.19 for the JPY sales activity of the BOJ. Ito and Yabu (2007) estimate a reaction function for the BOJ that even explains 30.9% of the variation, using an indicator of interventions instead of the actual size of interventions.

[47] The results for the USD/ILS forward contracts with other maturities are almost identical, so we omit them for the sake of brevity.

Table 6: Contemporaneous exchange rate regressions

(a) Panel A

Dependent variable: $\Delta \ln(\text{USDILS}_t)$ (in %)

	[1]: OLS	**[2]: CU-GMM**	**[3]: 2SLS**
Intercept	−0.0203***	−0.0273***	−0.0259***
	(−2.57)	(−2.16)	(−2.11)
FXI_t	0.55***	0.85***	0.84***
	(4.75)	(2.10)	(2.04)
$\Delta\text{EUR/USD}_{t-1,t}$	−0.41***	−0.41***	−0.41***
	(−23.51)	(−21.69)	(−21.43)
$\Delta\text{VIX}_{t-5,t}$	0.01***	0.01***	0.01***
	(4.31)	(3.45)	(3.50)
$\Delta\text{LIBOR}_{t-5,t}$	0.01	−0.01	−0.02
	(0.02)	(−0.03)	(−0.07)
Hansen J-statistic		1.79	
Hansen J-statistic p-value		0.94	

(b) Panel B

Dependent variable: $\Delta \ln(\text{NEER}_t)$ (in %)

	[1]: OLS	**[2]: CU-GMM**	**[3]: 2SLS**
Intercept	−0.0260***	−0.033***	−0.0310***
	(−3.19)	(−2.67)	(−2.48)
FXI_t	0.55***	0.82**	0.77*
	(4.43)	(2.02)	(1.88)
$\Delta\text{EUR/USD}_{t-1,t}$	0.01	0.01	0.01
	(0.74)	(0.64)	(0.53)
$\Delta\text{VIX}_{t-5,t}$	0.01***	0.005*	0.01***
	(2.17)	(1.69)	(2.05)
$\Delta\text{LIBOR}_{t-5,t}$	−0.04	−0.073	−0.07
	(−0.12)	(−0.14)	(−0.13)
Hansen J-statistic		7.32	
Hansen J-statistic p-value		0.29	

(c) Panel C

	Dependent variable: $\Delta \ln(\text{3M forward}_t)$ (in %)		
	[1]: OLS	[2]: CU-GMM	[3]: 2SLS
Intercept	−0.0180**	−0.027**	−0.02*
	(−2.27)	(−2.11)	(−1.82)
FXI_t	0.46***	0.720*	0.66
	(3.95)	(1.68)	(1.52)
$\Delta\text{EUR/USD}_{t-1,t}$	−0.33***	−0.333***	−0.33***
	(−18.00)	(−16.43)	(−16.07)
$\Delta\text{VIX}_{t-5,t}$	0.01***	0.011***	0.01***
	(4.22)	(3.48)	(3.49)
$\Delta\text{LIBOR}_{t-5,t}$	0.03	0.344	0.33
	(0.08)	(0.66)	(0.64)
Hansen J-statistic		4.546	
Hansen J-statistic p-value		0.603	

Notes: The daily log return of the USD/ILS spot rate (in percent), the nominal effective exchange rate ("NEER"; panel B), and the three-month USD/ILS forward rate ("3M Forward"; panel C) is regressed on an intercept, the size of interventions ("FXI_t"; in USD billions), the daily log return of the EUR/USD spot rate ("$\text{EUR/USD}_{t-1,t}$"; in percent), the one-week change in the VIX ("$\Delta\text{VIX}_{t-5,t}$"; in percentage points) and the one-week change of the USD LIBOR rate ("$\Delta\text{LIBOR}_{t-5,t}$"; in percentage points). In specification [1] and [2] standard OLS and the continuously updated GMM estimator (CU-GMM) are used. In specification [3], we report the two-stage least squares estimator (2SLS). For details about the set of instruments that are included in the CU-GMM, see Table 5. To assess whether the data in the CU-GMM is consistent with the imposed moment conditions, the Hansen J-test statistic of over-identifying restrictions is included. The t-statistics (in parentheses below the coefficients) are the Newey-West HAC corrected t-statistics. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively. The sample spans the period from January 1, 2013, to December 31, 2019.

The estimated coefficient that captures the effect of FX interventions on the three-month USD/ILS forward rate equals 0.72% and is only statistically significant at the 10% significance level. The value is 6%-10% smaller in size than the coefficient for the two spot rates. The difference, the so-called forward premium, is significantly different from zero.[48] Our result is at odds with the CIP condition that dictates that the spot and forward rates should move one-to-one, holding domestic and foreign interest rates constant.[49] Therefore, our finding suggests a potential arbitrage opportunity. A possible explanation for the arbitrage opportunity might be the existence of balance sheet-constrained banks and the herewith associated difficulty in obtaining dollar funding in the aftermath of the GFC[50] that makes it costly for banks to arbitrage the cross-currency basis.

Our results are also in line with the predictions of the model proposed by Amador et al. (2020). In their model the central bank of a small open economy (like Israel) can

[48] In Table B.1 in Appendix B, we confirm that the effect on the cross-currency basis is negative and statistically significant.

[49] Keep in mind that the USD purchases are sterilized by the BOI. Furthermore, as we use daily data, the daily change of the US risk-free interest rate is rather small.

[50] See the recent empirical literature that finds that a negative basis vis-à-vis the USD is observed in FX market since the GFC (for instance, Du et al. (2018) and Du and Schreger (2021)). In this case hedged synthetic USD funding via cross-currency swap markets is more expensive than borrowing USD directly in the US cash market.

choose an optimal exchange rate policy (in addition to the size of its balance sheet) that, nevertheless, leads to a violation of interest parity when the zero lower bound binds. In such a situation, they show that a central bank optimally sets interest rates to zero and carry out FXI in the spot FX market. All else equal, the implementation of this policy then generates the expectation of an appreciation of the domestic currency in the future. To see this and following Du et al. (2018), we include the market convention of the cross-currency basis, adjusting the label of the variables that compose this basis to the intervention regime that we analyze:

$$CCB_t = r_t^{US} - \left[r_t^{IL} - (f_t - s_t)\right], \tag{5}$$

where r_t^{US} denotes the log of (1 + 3-month USD LIBOR), r_t^{IL} the log of (1 + 3-month TELBOR), f_t the log of the 3-month USD/ILS forward rate and s_t the log of the 3-month USD/ILS spot rate.

According to the asset market approach to exchange rate determination, sterilized interventions imply that both interest rates r_t^{US} and r_t^{IL} remain unchanged (Villamizar-Villegas and Perez-Reyna, 2017). Therefore, the CCB can be expressed as

$$CCB_t \approx f_t - s_t. \tag{6}$$

As postulated by the Amador et al. (2020) model, the BOI's interventions will all else equal raise s_t and make the cross-currency basis more negative (positive in Amador et al. (2020), as they use the cross-currency basis with the opposite sign[51]). In our case, also the USD/ILS forward rate increases, but by a smaller amount. Hence, the BOI's intervention activity on average has widened the cross-currency basis, despite also affecting market expectations in the intended direction.

How do our estimated coefficients that quantify the effect of FX interventions on the spot rate compare to the estimates in other recent papers? Ribon (2017) has also analyzed the BOI's most recent intervention regime. Using monthly FX intervention data, she finds that interventions amounting to mUSD 830 contribute to a depreciation of the NEER that is larger on average by 0.6% compared to a trading day with no intervention activities. Re-scaling the size of interventions to make her results comparable to ours, her estimated coefficient corresponds to an estimated coefficient of 0.74, which is ≈ 10% lower than our estimate of 0.82 for the case of the NEER in Table 6. We note, however, that she examined a different period (2009–2015) than our study.

Compared to other papers that have analyzed the intervention activity of other central

[51]There are other papers that also use this alternative definition, see Du and Schreger (2016), Du, Im, and Schreger (2018) and Dedola et al. (2021), amongst others.

banks (see Section 1 for details), we find that our estimate of 0.85% and 0.82% is at the upper bound of other papers, reflecting a high effectiveness of the BOI's FX intervention activity in affecting the foreign value of the ILS in the desired direction by both historical and international standards. We hypothesize that the BOI's effectiveness may be due to the large size of the USD purchases in the period of interest. A comparison of the average size of FX interventions relative to domestic GDP indicates that this ratio is large by international standards. For instance, Table 2 in Fratzscher et al. (2019) indicates that countries that de jure have a free floating regime in place intervene by 0.02% of GDP on average per event day vs. 0.05% of GDP in the case of the BOI (see Table 2). The number increases to 0.03% and 0.05% for countries with pegs and broad or narrow bands, respectively. Our conjecture is further supported by the stylized facts about FX interventions and the determinants that explain their effectiveness, as identified by e.g. Fratzscher et al. (2019). Using a sample of daily data covering 33 countries from 1995 to 2011, these authors find that a key determinant of success is a large size of FX interventions (for instance in terms of domestic GDP). Last but not least, the more pronounced estimated coefficient in our study may partially also be related to the higher frequency of our data than in many previous studies, which better shields our results against the effect of confounding factors and/or reverse causality (Menkhoff et al., 2021).

When comparing the estimated coefficients using OLS versus CU-GMM, we see that these are larger in the latter case. The finding suggests that the inclusion of instruments is important to mitigate the potential negative bias in the estimated coefficients caused by endogeneity. As explained in Fratzscher (2005) and similar to our findings in Table 5, central banks usually intervene to "lean against the wind," that is to revert or contain a sustained trend of the foreign value of the domestic currency vis-à-vis a specific foreign currency.[52] Under these circumstances, endogeneity causes a downward bias in the estimated coefficients and OLS regressions tend to underestimate the actual effect of FX interventions.

Finally, note that the Hansen J-test statistic of over-identifying restrictions is statistically insignificant. This indicates that our GMM model is well specified, that is, the data that we use is consistent with the imposed moment conditions.

3.1.3 Econometric assessment of the longer-term effect

The empirical evidence on FX interventions carried out by other central banks shows that the effect of FX interventions on FX spot rates is rather short-lived.[53][54] Therefore, we

[52] And sometimes also to stabilize the targeted spot rate by dampening its volatility.

[53] See Galati et al. (2005) and the survey in Villamizar-Villegas and Perez-Reyna (2015).

[54] From the previously cited discussion in Miyajima (2013) we know that one possible explanation for this short-lived effect may be that central banks intervene too often, thereby not allowing financial market

now assess how persistent the effect of the BOI's intervention activity on the foreign value of the ILS is.[55] To this end, we analyze the relation between the size of the USD purchases and following exchange rate returns using long-horizon regressions for the USD/ILS spot rate, the NEER, and the three-month USD/ILS forward rate. Specifically, we regress their log-returns from t to to $t + h$ on the intervention on day t, where h – the length of the forecast horizon – ranges from one up to ten trading days.[56] As we have overlapping data, we use the correction suggested by Hjalmarsson (2011)[57] and divide the standard t-statistic by the square root of the corresponding forecast horizon. We also correct for the potential bias in the estimated coefficients when running long-horizon predictive regressions, as suggested in a recent paper by Boudoukh et al. (2021). As controls, we use the variables that we used in Table 5, but adjust the changes in the controls for the different lengths of the forecast horizon. The results are displayed in Table 7.

The results suggest that the effect persists in the NEER, the USD/ILS, and the three-month forward rate for at least two days. However, only in the NEER we do find persistence for up to five trading days. We also see that the point estimates stay relatively high even at the tenth trading day after the first intervention (and in untabulated results, the point estimates remain high for longer trading days). But, the large noise in the FX market doesn't enable us to say anything about the persistence beyond five days in the NEER. Our results therefore differ from the findings in Caspi et al. (2018) who analyze the effect of FX intervention shocks (i.e. the surprise component of FX interventions) and document that their impulse response functions (displaying the cumulative change in the NEER) become insignificant only after about two calendar months.

Regarding the results of the forward rates, as we remarked in Table 6, the forward rate reacts less than the NEER and the USD/ILS to an intervention by the BOI. The long-run regressions in Table 7 do not indicate that the subdued reaction is due to a "sluggish" adjustment in the forward rate. Therefore, the BOI's intervention activity indeed makes the cross-currency basis more negative.

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participants to effectively learn about the intervention activity.

[55] See online Appendix F, where we explain to what extent our long-horizon regression captures the longer-term effect of the size of interventions on day t.

[56] We acknowledge that we could have used the local projection IV methodology (e.g., the local projection IV (LP-IV) approach in Ramey and Zubairy (2018)) to mitigate possible attenuation bias in our regressions. However, the results in Table 6 show that there is a significant increase in the standard errors of the effect of intervention when using the CU-GMM estimator and the 2SLS, compared to the OLS estimator. Given the fact that long-horizon regressions add noise, it would be hard to statistically detect whether the effect of intervention persists using the LP-IV approach (which we also confirm in untabulated results). Therefore, we use the standard OLS approach which is probably more conservative.

[57] Also recommended by Boudoukh, Israel, and Richardson (2021) due its superior finite sample properties compared to alternative adjustments. For instance, the widely used Newey-West HAC standard errors inflate the t-statistics. Our results are thus more conservative than papers that use these type of adjustments.

Table 7: Long-horizon predictive regressions: regressing multi-period horizon exchange rate returns on the contemporaneous intervention volume

	Dependent variable:		
Period (h)	$\Delta\ln(\mathbf{USDILS}_{t+h})$ (%)	$\Delta\ln(\mathbf{NEER}_{t+h})$ (%)	$\Delta\ln(\mathbf{3M\ forward}_{t+h})$ (%)
1	0.680***	0.665***	0.685***
	(3.09)	(2.99)	(3.35)
2	0.543*	0.704**	0.546*
	(1.69)	(2.15)	(1.71)
5	0.666	0.745*	0.620
	(1.28)	(1.68)	(1.17)
10	0.833	1.069	0.892
	(0.81)	(1.27)	(0.82)

Notes: The daily log returns (all in percent) of the USD/ILS spot rate (column 2), the NEER (column 3) and the three-month USD/ILS forward rate (column 4) are regressed on the time t intervention volume FXI_t (in USD billion). The dependent variable in the h-period regressions is $\Delta\ln(X_{t+h}/X_{t-1})$ with $X \in \{\text{USDILS, NEER, three-month forward}\}$. The regression is carried out with overlapping data. In the regression, we use the variables of Table 5 as additional controls, adjusting them accordingly for the varying length of the forecast horizon. We adjust the coefficients due to the bias in long-horizon regressions (see Boudoukh et al. (2021)). The t-statistics (in parentheses below the coefficients) are the OLS t-statistics divided by the square root of the forecasting horizon to correct for the bias caused by using overlapping data (see Hjalmarsson (2011)). *, **, and *** denote significance at the 10%, 5%, and 1% levels respectively. The sample spans the period from January 1, 2013 to December 31, 2019.

3.2 Effect of interventions on the higher moment expectations

In Section 3.2.1, we extend our analysis to assess to what extent option markets price in future interventions, as reflected in the price quotes of the three FX option strategies that we consider (the ATMVs, RRs, and BF spreads). The analysis allows us to understand how option markets' expectations are affected by FX interventions under a secret intervention regime. We also analyze how (if at all) FX interventions affect the risk-neutral tail probabilities of the distribution of the future USD/ILS spot rate as reflected by the RND extracted from the price quotes of USD/ILS options (Section 3.2.2) and the aforementioned price quotes contemporaneously and over longer horizons (Section 3.2.3). We focus on those option contracts with maturities ranging from one month ("1 M") to twelve months ("12 M"). This granularity helps us analyze how option market participants view the long-term effect of FX interventions.

For example, consider the RR option contracts, scaled by the corresponding ATMV,[58] such that it is a proxy for the implied skewness of the RND.[59] If we find that the price quote

[58] By scaling, the RR no longer depends on the prevailing level of the option-implied volatility curve (Jurek, 2014).

[59] See online Appendix G.4 for details.

of the scaled one-month RR is adjusted upward, while the contracts with longer maturities are not, it suggests that financial markets believe that the BOI's intervention activity has no impact on the option-implied skewness of the future USD/ILS exchange rate[60] beyond the one-month horizon. However, before running these analyses, we will discuss the role of option markets in providing information beyond what is already reflected in spot markets in the next section.

Informational externalities. The FX spot rate is equal to the discounted value of its future fundamental value according to the asset pricing model of FX rates (Engel and West, 2005), which implies that the spot rate is forward-looking, similar to option contracts. Moreover, ruling out arbitrage opportunities means that the information content of FX options is equal to the information content of the underlying exchange rate, as a riskless hedging portfolio replicates the former. In this case, what information do we expect to gain by analyzing options data beyond the information that is already priced in the spot rate? The seminal work of Grossman (1988) shows (when applied to the FX market) that option prices reveal information about the share of financial market participants that would potentially sell (or buy) a specific currency in the case of unexpected large spot FX rate movements, for example, when currency crash risks (random jump risks) materialize (which are risks that can be insured by entering a risk reversal (BF spread[61]) contract). Therefore, from a theoretical perspective, we know that looking at option markets allows us to learn about the financial market's perceived (preference-weighted) uncertainty concerning the future spot exchange rate and how this uncertainty changes when the BOI intervenes.

Market imperfections. In addition, with limits to arbitrage (e.g. due to balance-sheet constrained banks), derivatives are no longer redundant assets. In this case, the RND extracted from FX options reflects risk premia and expectations about the higher-order moments of the distribution of the future FX spot rate. Options then help to complete the market (Figlewski, 2018). Another source that may lead to market incompleteness is due to even more practical limitations (e.g., the existence of trading costs) that do not allow option writers to fully remove their risk exposures (e.g., delta exposures when delta hedging these risks). As recently shown by Tian and Wu (2021), option writers cannot fully hedge their risk exposures for U.S. stocks in practice and therefore demand a premium for bearing these risks. Specifically, Tian and Wu (2021) identify three relevant

[60] And its risk characteristics as reflected in the higher moments of the RND.

[61] Alternatively, the (scaled) risk reversals can be used to shield against jump risks. In line herewith, in the lottery-preference literature, ex ante skewness is used as a proxy for the "lottery-like characteristics of options", see e.g. Boyer and Vorkink (2014).

risk components, where one is the premium demanded for bearing random jump risk. In the case of the BOI, market participants may consider FXI as random jump risks, as the BOI intervenes secretly and they may have learned over time that the BOI's FXI are associated with a relatively large USD/ILS spot rate response (e.g., due to the findings in Ribon (2017)). Have in mind that RRs provide insurance against jump risks. Therefore, central banks may affect option markets by affecting the market's perception about jump risks. We will later see that this is indeed the case for the USD/ILS risk reversals that increase in anticipation of future FXI. This also suggests that understanding to what extent FXI affect the option-implied skewness and kurtosis is of interest for FX risk managers and FX option writers.

To conclude this section, looking at the options market can provide a better understanding of the source of the changes in the RND and, thereby, of the source of changes in the USD/ILS spot rate due to changes in higher moment expectations. Questions that we can answer by looking at the USD/ILS options market include, for instance: on the days the BOI intervenes (and, as we showed, causes a depreciation), does it also affect the price of insurance against FX crash risk? Did the RND become more left-skewed over time due to the BOI's continuous intervention activity? Are there fat tails? These are questions that can only be answered by examining the options market.

3.2.1 Relationship between the three option strategies and future interventions

We begin by assessing the adequacy of using ATMVs, RRs, and BF spreads as additional explanatory variables to help explain the variation in the size of future FX interventions. Formally, we regress the FX intervention data on the one-day lagged[62] two-week change of the equally weighted mean of the scaled 10- and 25-Δ RR ("$\Delta\text{RR}_{t-11,t-1}$"), the scaled[63] BF spreads ("$\Delta\text{BF}_{t-11,t-1}$") and the ATMV ("$\Delta\text{ATMV}_{t-11,t-1}$") as controls. We control for the contemporaneous change in the spot rate to control for the aforementioned "systematic" positive correlation between changes in the USD/ILS exchange rate and changes in the quoted prices of the RRs and BF spreads that is observed in practice.[64] In other words, we want to make sure that the options market has information beyond the contemporaneous change that is due to changes of the spot rate. The results are displayed in

[62]We lag the regressors to remove the contemporaneous effect that the BOI's USD purchases have on the USD/ILS exchange rate.

[63]By scaling, the quoted prices of these two option strategies are proportional to the implied skewness and excess kurtosis of the USD/ILS RND, see online Appendix G.4 for details.

[64]See footnote 41. In theory, if interventions do not affect the at-the-money volatility level and the expected skewness (excess kurtosis) of the distribution of the future FX spot rate, the price quotes of the RRs (BFs) should not change between two following trading days, as the moneyness of the options that constitute these strategies should not change from one day to the other (see online Appendix G.3).

Table 8. In all the specifications, we use the variables (controls and instruments) described in Table 5 as controls.

Table 8: Relationship between FXI and lagged risk reversals, butterfly spreads and at-the-money implied volatilities

	Dependent variable: $\mathbf{FXI_t}$				
	1 M	**3 M**	**6 M**	**9 M**	**12 M**
Intercept	0.012***	0.012***	0.012***	0.012***	0.012***
	(5.76)	(5.84)	(5.82)	(5.76)	(5.69)
$\Delta\overline{\text{RR}}_{t-11,t-1}$	0.104	0.159**	0.172*	0.186*	0.209*
	(1.56)	(2.09)	(1.71)	(1.79)	(1.82)
$\Delta\overline{\text{BF}}_{t-11,t-1}$	0.327	−0.026	−0.105	−0.246	−0.399
	(0.96)	(−0.09)	(−0.37)	(−0.91)	(−1.28)
$\Delta\text{ATMV}_{t-11,t-1}$	0.002	0.004	0.005	0.002	−0.001
	(0.38)	(0.67)	(0.90)	(0.41)	(−0.11)
Controls	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	6.70	6.70	6.71	6.69	6.75

Notes: The size of daily FX interventions ("FXI_t", in USD billion) is regressed on the one-day lagged two-week change of the equally weighted mean of the scaled 10- and 25-delta USD/ILS risk reversals ($\Delta\overline{\text{RR}}_{t-11,t-1}$), the scaled 10- and 25-delta USD/ILS butterfly spreads ($\Delta\overline{\text{BF}}_{t-11,t-1}$) and the at-the-money USD/ILS options ($\Delta\text{ATM}_{t-11,t-1}$). We consider five option maturities in total, ranging from one month ("1 M") to twelve months ("12 M"). As additional controls, we use the variables described in Table 5. The t-statistics (in parentheses below the coefficients) are the Newey-West HAC corrected t-statistics. *, **, and *** denote significance at the 10%, 5%, and 1% levels respectively. The sample spans the period from January 1, 2013 to December 31, 2019.

We note several things. On average, interventions amounting to mUSD 12 are expected on every trading day. A large amount of the FX intervention volumes are therefore unrelated to changes in the quoted prices of the three options strategies. The results concerning these strategies confirm the finding, as many coefficients are insignificant. An exception are those coefficients associated with the weighted RRs, a measure of the skewness of the distribution. Most of the coefficients of the RR are significant (although most are only marginally significant) and positive, reflecting a more pronounced tilt of the expected future USD/ILS spot rate towards large USD appreciation surprises in the two weeks prior to an intervention episode. The market adjusts the price quotes of the RRs across all five maturities upward in anticipation of higher future interventions. Interestingly, the upward adjustment across all maturities implies that market participants perceive the upcoming intervention activity as having an effect lasting for at least one year.

One could alternatively interpret this finding in the sense that the BOI seems to "lean with the wind" in the USD/ILS options market, intervening when the implied skewness increases, which could indicate an additional FX intervention strategy triggering FX interventions based on option market information. However, we find this interpretation less convincing, as such a strategy would be hard to implement: notice that the coefficient on the RR reflects the marginal increase of the RR after controlling for changes in the USD/ILS spot rate. That is, we'd need to believe that the BOI monitors the prices of RRs controlling for the effect that FX interventions have on the USD/ILS spot rate.

Regarding the magnitude of the effect, an increase of the RR by one percentage point is associated with a FX intervention volume which is larger by between mUSD 104 ("1 M") and mUSD 209 ("12 M"). The finding that the size of the estimated coefficients (i.e., reflecting the anticipation of future FXI) increases with option maturities is in line with the simulation results in Figlewski (1989) who shows that the potential price impact of market imperfections increases with option maturities. However, the standard deviation of the adjusted RRs is decreasing with option maturities. An increase of the one- to twelve-month RRs by one standard deviation is associated with FX interventions which are only mUSD 4 larger. As expected, the marginal information in the RRs is relatively small but significant, which indicates the sophistication of the option market.

To conclude this section: while the coefficients associated with the RRs are significant, this is not true for the BF spreads and the ATMV. Therefore, option market participants seem to only price crash-risks related to a large USD appreciation ("unidirectional crash risk") – the BOI therefore succeeds in affecting higher moment market expectations in the intended direction.

3.2.2 Risk-neutral tail probabilities and future interventions

This section analyzes the relation between the tails of the USD/ILS RND and future interventions. Estimating the tail probabilities (or crash-risk probabilities) serves two purposes: 1. In the previous section, we found a positive relation between the option-implied skewness of the RND and following interventions, after controlling for the effect of these interventions on the USD/ILS spot rate. The RR can also be considered as the difference between the risk-neutral probability of a large depreciation minus the risk-neutral probability of a large appreciation, where both probabilities are weighted by the corresponding intrinsic values that compose this option strategy. Therefore, disentangling the RND components will help us to understand the source of the relation between the RR and future interventions. 2. Probabilities are more intuitive to understand than changes in option prices or option-implied higher moments.

We therefore extract the USD/ILS RND for each trading day and for each of the five maturities that we examine. To this end, we use the methodology suggested by Figlewski (2009), which we modify so that we can apply it to FX options, see online Appendix H for details. As we have five different maturities, we have to be careful about the representativeness of the thresholds that we use to determine the tails of the RND. For example, a 3% depreciation may be substantial within a horizon of one month, but not for a horizon of one year. Therefore, for each maturity, the thresholds are chosen such that they are about two and a half standard deviations away from the average ATMV during the period under review. The calculation amounts to 5%, 8%, 10%, 13% and 20% for the one-month up to the one-year horizon. We acknowledge that in converting the price quotes of the option contracts to probabilities, we introduce measurement errors. To reduce the potential bias caused by these errors, we use the price quotes of the RR and the BF contracts as instruments to estimate the relationship between the lagged tail probabilities and interventions.[65]

The results are presented in Table 9. All the estimated coefficients have the expected sign, although they are not statistically significant. However, we find it reassuring that the estimated coefficients are grosso modo similar across maturities. The results show that a 1 percentage point decrease in the left tail (that is, a lower probability of a large appreciation of the ILS) is associated with an anticipated intervention that is on average mUSD 84 ("1 M") to mUSD 277 higher ("3 M"). Similarly, a 1 percentage point increase in the right tail (higher probability of a large depreciation of the ILS) is associated with an intervention volume that is mUSD 67 ("12 M") to mUSD 366 higher ("3 M"). The results imply that market participants attach both a higher risk-neutral probability to a

Table 9: First-stage regressions using lagged RND tail probabilities

	Dependent variable: FXI_t				
	1 M	**3 M**	**6 M**	**9 M**	**12 M**
Intercept	0.013***	0.014***	0.013***	0.013***	0.013***
	(5.49)	(5.31)	(6.17)	(5.50)	(5.96)
ΔProb. of appreciation$_{t-11,t-1}$	−0.084	−0.277	−0.172	−0.200	−0.263
	(−0.68)	(−1.09)	(−1.12)	(−1.63)	(−1.40)
ΔProb. of depreciation$_{t-11,t-1}$	0.107	0.366	0.203	0.204	0.067
	(1.46)	(1.61)	(1.27)	(1.35)	(0.54)
Controls	Yes	Yes	Yes	Yes	Yes
Hansen J-statistic	1.375	1.453	1.888	0.991	1.002
Hansen J-statistic p-value	0.503	0.484	0.389	0.609	0.606

Notes: The table presents the results of regressing the daily intervention volume ("FXI_t", in USD billion) on the one-day lagged two-week change of the probability of a strong appreciation of the ILS ("ΔProb. of appreciation$_{t-11,t-1}$", in percentage points) and of a strong depreciation of the ILS ("ΔProb. of depreciation$_{t-11,t-1}$", in percentage points) for five contract maturities, ranging from one month ("1 M") to twelve months ("12 M"). In all the specifications, we also use both the one-day lagged one-week log return and the one-day lagged one-month log return of the NEER and the one-day lagged one-day change of the VIX as control variables. The t-statistics (in parentheses below the coefficients) are the Newey-West HAC corrected t-statistics. *, **, and *** denote significance at the 10%, 5%, and 1% levels respectively. The sample spans the period from January 1, 2013 to December 31, 2019.

strong depreciation and a lower risk-neutral probability to a strong appreciation before

[65]Specifically, for the one-month contract, we use the one-month to twelve-month RR and BF, and so on. We estimate the regression using 2SLS regression.

the BOI intervenes.

3.2.3 Relationship between option strategies and contemporaneous and future interventions

In the previous two sections, we have analyzed the relationship between the price quotes of the scaled USD/ILS option strategies, their implied crash-risk probabilities, and future interventions. This section examines how the BOI's interventions affect the price quotes of these option strategies contemporaneously or with a lag, running long-horizon OLS regressions. The regression allows us to understand how the expected higher moments of the distribution of future USD/ILS spot rates adjust over more extended periods as a response to the BOI's intervention activity.

The results are presented in Table 10, where we control again for the contemporaneous correlation between the option price quotes and the spot exchange rate (see footnote 32 for the motivation). Otherwise, our results might be affected by this correlation, which is unrelated to FX interventions. Our results indicate that there is no contemporaneous relation between the size of FX interventions and the price quotes of the scaled option strategies at the 5% significance level. Examining the different horizons, we find no significant relation between the size of contemporaneous FX interventions and future intervention volumes. This finding is in line with most papers in this strand of literature.

How should we interpret these results? We argue that the results do not imply that the BOI's intervention has no effect on market expectations after they happen. Recall that we report in our empirical analysis that there is a large depreciation of the ILS in both the USD/ILS spot and the USD/ILS forward market on those days when the BOI intervenes, with no signs of a following reversal of this initial effect. The fact that we don't find any change in the higher moments of the USD/ILS RND therefore implies that this distribution is only locationally shifted to the right (that is, in the direction of higher future USD/ILS spot rates), leaving all other option-implied moments unchanged. In other words, the market's perceived uncertainty with respect to the future spot exchange rate is unaffected. Also recall that the price quotes of the scaled USD/ILS option strategies are adjusted in advance, reflecting the market's perception of higher future intervention volumes (Section 3.2.1), while these price quotes are not adjusted when these interventions are actually carried out (this section). We interpret this "asymmetry" (or the statistically significant anticipation of future intervention volumes) as evidence that the BOI is successful in shaping market expectations. This finding may also be related to the fact that the BOI publishes each month the previous month's intervention volumes in the USD/ILS spot market, which allows market participants to estimate a time series model to predict the expected intervention volumes for the following months and quarters. This finding may also be the mirror image of the BOI's intensive intervention activity that allows option market participants to learn over time that the BOI's commitment to intervene in the USD/ILS spot market is credible. We conjecture that the fact that the BOI's intervention activity to date has been accompanied by monthly updates on the actual total monthly intervention volumes that allows financial market participants to calibrate a time series model that allows them to predict the expected size of FX interventions may in part explain why previous studies have found only a weak relation between interventions in spot FX markets and their effect on FX derivatives markets.

Table 10: Multi-period change in the price quotes of the risk reversals, butterfly spreads and at-the-money implied volatility options regressed on interventions

(a) Panel A

	Dependent variable: $\Delta(\overline{\mathbf{ATMV}}_{t+h})$				
Period (h)	**1 M**	**3 M**	**6 M**	**9 M**	**12 M**
0	0.0436	0.0256	0.0143	−0.0028	0.0036
	(0.89)	(0.86)	(0.68)	(−0.15)	(0.20)
1	0.0932	0.0481	0.0291	−0.0001	−0.0072
	(1.00)	(0.85)	(0.72)	(0.00)	(−0.26)
5	0.1104	0.0824	0.0556	0.0286	0.0072
	(0.55)	(0.63)	(0.62)	(0.39)	(0.11)
10	0.1929	0.1975	0.1364	0.1164	0.0899
	(0.43)	(0.70)	(0.69)	(0.72)	(0.64)

(b) Panel B

	Dependent variable: $\Delta(\overline{\mathbf{RR}}_{t+h})$				
Period (h)	**1 M**	**3 M**	**6 M**	**9 M**	**12 M**
0	−0.0024	−0.0005	0.0002	−0.0002	0.0009
	(−0.95)	(−0.19)	(0.08)	(−0.05)	(0.32)
1	−0.0027	−0.0003	0.0003	0.0002	0.0002
	(−0.59)	(−0.06)	(0.08)	(0.04)	(0.04)
5	−0.0023	0.0020	0.0018	0.0015	0.0025
	(−0.20)	(0.21)	(0.21)	(0.14)	(0.32)
10	0.0146	0.0171	0.0154	0.0099	0.0154
	(0.73)	(0.85)	(0.82)	(0.57)	(0.86)

(c) Panel C

	Dependent variable: $\Delta(\overline{\mathbf{BF}}_{t+h})$				
Period (h)	**1 M**	**3 M**	**6 M**	**9 M**	**12 M**
0	-0.0005	-0.0006	0.0002	0.0002	0.0013
	(-0.40)	(-0.31)	(0.10)	(0.11)	(0.61)
1	0.0008	-0.0013	-0.0018	-0.0020	-0.0012
	(0.32)	(-0.63)	(-0.76)	(-0.88)	(-0.49)
5	0.0004	-0.0023	-0.0030	-0.0035	-0.0012
	(0.11)	(-0.39)	(-0.43)	(-0.56)	(-0.21)
10	0.0048	0.0024	0.0017	0.0016	0.0017
	(0.70)	(0.43)	(0.30)	(0.30)	(0.28)

Notes: Panel A, B, and C present the results of overlapping long-horizon regression of the change in the equally weighted average of the 10- and the 25-delta USD/ILS at-the-money volatility ($\overline{\mathrm{ATM}}_{t+h} - \overline{\mathrm{ATMV}}_t$), risk reversals ($\overline{\mathrm{RR}}_{t+h} - \overline{\mathrm{RR}}_t$, and butterfly spreads $\overline{\mathrm{BF}}_{t+h} - \overline{\mathrm{BF}}_t$) over a period of h periods, and for five different maturities, ranging from one month ("1 M") to one year ("12 M") on lagged FX intervention volumes (in USD billion) at time t. When the forecast horizon h is zero, we use the change of the quoted prices of the corresponding option strategy between time $t-1$ to t, that is, we run a contemporaneous regression. We adjust the coefficients due to the bias in long-horizon regressions (see Boudoukh et al. (2021)). The t-statistics (in parentheses below the coefficients) are the OLS t-statistics divided by the square root of the forecasting horizon to correct for the bias caused by using overlapping data (see Hjalmarsson (2011)). *, **, and *** denote significance at the 10%, 5%, and 1% levels respectively. The sample spans the period from January 1, 2013 to December 31, 2019 . *, **, and *** denote significance at the 10%, 5%, and 1% levels respectively.

4 Conclusion

Since early 2008, the Bank of Israel (BOI) has periodically been intervening in the USD/ILS spot market to weaken the foreign value of the ILS vis-à-vis the USD. The present paper analyzes the effectiveness of this relatively long intervention episode. We find that interventions amounting to USD 1 billion are on average associated with a depreciation of the ILS that is larger by approximately 0.85% percentage points compared to a trading day without interventions. Our estimated coefficient is at the upper bound of the estimated impact in other studies. We conjecture that the higher effectiveness may be related to the large size of interventions by international standards and the higher frequency of our intervention data compared to many previous studies, which better shields our estimated coefficients against the effect of confounding factors and/or reverse causality (Menkhoff et al., 2021).

With regard to how the BOI's interventions have affected the USD/ILS option market, our paper shows that looking at FX option markets adds information about the effectiveness of FX interventions. Specifically, our paper finds that (1) the price quotes of the USD/ILS risk reversals – an option strategy that provides insurance against currency crash-risk (Jurek, 2014) and reflects a more pronounced tilt towards a stronger USD when it increases – adjust in the expected direction in anticipation of higher future interventions. (2) On the contrary, the higher moments (volatility, skewness, and kurtosis) of the risk-neutral density (RND) – proxied by the scaled price quotes of USD/ILS options – do not change as a response to the BOI's interventions. This lack of adjustment of the higher moments of the RND, combined with the large effect that the BOI's interventions have on the USD/ILS forward rate, implies that the BOI locationally shifts the whole distribution towards higher USD/ILS values without affecting the options market view on the higher-order risks. Crash risk, for instance, is unaffected. The options market seems to price in future interventions (see result (1)), while the price quotes are not adjusted when these interventions are actually carried out. It appears that the BOI's intensive intervention activity has permitted option markets to learn over time that the BOI's commitment to its intervention regime is highly credible, which has allowed the BOI to shape market expectations in the intended direction.

We also examine the effect that interventions have on the USD/ILS forward rates, the first moment of the RND. We find that interventions increase the price of the USD/ILS 3-month forward rate by 0.72%, which is less than the effect on the USD/ILS spot rate. The lower effect implies that the intervention activity widens the cross-currency basis. To the best of our knowledge and as explained in the main body of the paper, there are reasons to believe that we are the first to empirically show that FX interventions indeed widen the deviation from covered interest, as predicted by Amador et al. (2020), who propose a framework to study the problem of a central bank in a small open economy that pursues an exchange rate policy that leads to a violation of interest parity when the zero lower bound binds. We thereby contribute to the recently revived strand of literature that examines deviations from covered interest rate parity.

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Appendix

A Specification analysis of first-stage regression

This appendix shows the results of the first-stage regression with different specifications in Table A.1. Specification [1] shows that the one-day lagged daily FXI is significant, but not the two-day lag. In specification [2], we add a dummy that equals one if the BOI intervened in the past week. We also add log two-day, two weeks, and three months returns of the USD/ILS FX rate with different lag structures and $\Delta\mathrm{MA(USD/ILS)}_{t-1}$, which is defined as the difference between the USD/ILS rate and its one-year moving average. The results reveal that the latter doesn't have any explanatory power, unlike the log USD/ILS returns series.

Specification [3], however, shows that a model with a higher explanatory power in terms of the adjusted coefficient of determination is possible when using the lagged NEER instead of the USD/ILS FX rate – the higher explanatory power is due to the higher significance of the one-day lagged quarterly NEER return. In specification [4], the specification we use in the paper, we add the net ILS spot market purchases by non-residents and domestic institutional investors, the change in the 5-year CDS, and the VIX. With regards to flows by domestic and institutional investors, these two sectors have recently received significant attention from the BOI[66] and have been jointly identified as one of the "culprits" for the sustained appreciation trend of the ILS in the last years. The results suggest that a higher net demand for ILS – if these two sectors sell foreign currencies to buy ILS on a net basis, this variable is negative – is associated with higher FX interventions. However, the coefficient is numerically small while being statistically insignificant. With regards to the CDS and the VIX, although insignificant, untabulated results show that they increase the adjusted R-squared significantly.

Last, specification [5] reveals that the weekly change in the one-month USD LIBOR rate and the one-month TELBOR rates is not statistically significant.

[66]See e.g. Chapter 3 in the Bank of Israel yearly report 2020 and the Bank of Israel Financial Stability Report for the second half of 2020.

Table A.1: First-stage regression specification analysis

	[1]	[2]	[3]	[4]	[5]
Controls					
Intercept	0.015***	−0.007	−0.007	0.012***	0.012***
	(6.95)	(−0.33)	(−0.31)	(5.83)	(5.71)
ΔEUR/USD$_{t-1,t}$	0.011***	0.012***	0.011***	0.010***	0.010***
	(2.61)	(2.72)	(2.71)	(2.32)	(2.40)
ΔVIX$_{t-5,t}$	0.0000	0.0003	0.0003	0.0001	0.0001
	(0.10)	(0.57)	(0.64)	(0.14)	(0.16)
ΔLIBOR$_{t-5,t}$	0.107	0.113	0.118	0.146	0.062
	(1.26)	(1.33)	(1.38)	(1.64)	(0.18)
Instruments					
FXI$_{t-1}$	0.191***	0.179***	0.175***	0.170***	0.178***
	(4.31)	(4.13)	(4.04)	(3.81)	(3.95)
FXI$_{t-2}$	−0.016				
	(−0.53)				
$\mathbb{1}_{\{\text{FXI}_{t-6,t-1}>0\}}$	0.009**	0.007*	0.008**	0.010**	0.009**
	(2.04)	(1.71)	(2.04)	(2.32)	(2.25)
ΔUSD/ILS$_{t-3,t-1}$		−0.011**	−0.006		
		(−2.30)	(−1.01)		
ΔUSD/ILS$_{t-13,t-3}$		−0.004***	0.000		
		(−2.46)	(−0.12)		
ΔUSD/ILS$_{t-61,t-1}$		−0.001**	−0.001	−0.002***	−0.002***
		(−2.02)	(−1.12)	(−3.06)	(−3.00)
ΔMA(USD/ILS)$_{t-1}$		0.006	−0.005		
		(1.02)	(−0.92)		
ΔNEER$_{t-3,t-1}$			−0.008	−0.013***	−0.015***
			(−1.43)	(−3.16)	(−3.65)
ΔNEER$_{t-13,t-3}$			−0.004	−0.004*	−0.003*
			(−1.25)	(−1.90)	(−1.73)
ΔNEER$_{t-61,t-1}$			0.000		
			(−0.17)		
ΔCDS$_{t-21,t-1}$				−0.0004	−0.0004
				(−1.55)	(−1.56)
For. and inst. flows$_{t-2,t-1}$				−0.00001	
				−1.198	
ΔVIX$_{t-11,t-1}$				0.0004	0.0004
				(0.79)	(0.74)
ΔTELBOR$_{t-6,t-1}$					−0.035
					(−0.76)
ΔLIBOR$_{t-6,t-1}$					0.092
					(0.26)
Adjusted R^2	4.70	6.62	6.81	7.28	7.15

Notes: The dependent variable is the size of interventions ("FXI_t") in USD billions, available on a daily basis from January 1, 2013 to December 31, 2019. The t-statistics (in parentheses below the coefficients) are the Newey-West HAC corrected t-statistics. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

B Effect of daily intervention on the cross-currency basis

Table B.1: Contemporaneous exchange rate regressions

	Dependent variable: Δ (3M basis$_t$) (in %)		
	[1]: OLS	**[2]: CU-GMM**	**[3]: 2SLS**
Intercept	0.000	0.001	0.002
	(0.49)	(0.56)	(0.82)
FXI_t	-0.033*	-0.089*	-0.115*
	(-1.91)	(-1.66)	(-1.83)
$\Delta EUR/USD_{t-1,t}$	0.001	0.001	0.002
	(0.34)	(0.32)	(0.55)
$\Delta VIX_{t-5,t}$	-0.001	-0.001	-0.001
	(-1.28)	(-1.17)	(-1.08)
$\Delta LIBOR_{t-5,t}$	0.046	0.154*	0.153*
	(1.00)	(1.88)	(1.85)
Hansen J-statistic		3.040	
Hansen J-statistic p-value		0.804	

Notes: The daily difference of the three-month USD basis (in percentage points, annualized) is regressed on an intercept, the size of interventions ("FXI_t"; in USD billions), the daily log return of the EUR/USD spot rate ("$EUR/USD_{t-1,t}$"; in percent), the one-week change in the VIX ("$\Delta VIX_{t-5,t}$"; in percentage points) and the one-week change of the USD LIBOR rate ("$\Delta LIBOR_{t-5,t}$"; in percentage points). In specification [1] and [2] standard OLS and the continuously updated GMM estimator (CU-GMM) are used. In specification [3], we report the two-stage least squares estimator (2SLS). For details about the set of instruments that are included in the CU-GMM, see Table 5. To assess whether the data in the CU-GMM is consistent with the imposed moment conditions, the Hansen J-test statistic of over-identifying restrictions is included. The t-statistics (in parentheses below the coefficients) are the Newey-West HAC corrected t-statistics. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively. The sample spans the period from January 1, 2013, to December 31, 2019.