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Estimated Natural Rate of Interest in an Open Economy: The Case of Israel

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Estimated Natural Rate of Interest in an Open Economy:
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Abstract

The new Keynesian framework as presented in Clarida et al. (2002) suggests that in an open economy, the natural rate of interest consists of a local component (the expected growth of domestic total factor productivity) and a global component (the expected growth of world output). We estimate an augmented Taylor-type rule for Israel and confirm that the above-mentioned components contain valuable information about the monetary interest rate. In particular, a large part of the decline in the monetary interest rate in 2008–2009 is explained by the exceptional decline in world growth. With regard to the other and more traditional components of the rule, we find a high and significant response of the monetary interest rate to the inflation gap, the output gap, and the real exchange rate gap.

JEL Codes: E52, E58.

אמידת הריבית הטבעית למשק פתוח: יישום לישראל

דוד אלקיים וגיא סגל

תקציר

התיאוריה הניאו-קיינסיאנית למשק פתוח, כפי שמוצגת אצל (2002) .Clarida et al, גורסת שבמשק פתוח הריבית הטבעית מורכבת מרכיב מקומי (הגידול הצפוי בפריון הכולל) ומרכיב גלובלי (הגידול הצפוי בצמיחה העולמית). אנו אומדים כלל טיילור מורחב לישראל ומוצאים שאכן שני הרכיבים שלעיל מכילים אינפורמציה חשובה ביחס לריבית המוניטרית. במיוחד, חלק משמעותי מהירידה החדה שחלה בריבית המוניטרית בשנים 2008-2009 מוסבר בגורם הגלובלי – ירידה ניכרת של קצב הצמיחה העולמי. ביחס ליתר המשתנים היותר מסורתיים המופיעים בכלל הנאמד נמצאה תגובה חזקה של הריבית המוניטרית לפער האינפלציה, לפער התוצר ולפער שער החליפין הריאלי.

1. Introduction

According to the classic Taylor rule (Taylor, 1993) the interest rate responds positively to the inflation gap, the output gap, and to a (constant) "equilibrium" real interest rate. Under the Taylor rule the equilibrium real rate can be interpreted as the interest rate that fits a situation where the inflation rate is on target and the output gap is closed. A possible drawback of the implementation of the classic Taylor rule is that theory suggests that the equilibrium real rate of interest is not constant but heavily depends on several key variables.[1] An important and related concept in the new Keynesian (NK) framework is that of natural rate of interest (henceforth, NRI), i.e., the interest rate that would have prevailed in the absence of nominal rigidities. The optimal monetary policy in the canonical NK model can be represented as an interest rate rule in which the interest rate responds positively to the NRI and to expected inflation.[2]

In a closed economy the main determinants of the NRI are the expected growth of potential output and households' impatience to consume. In an open-economy setting the NRI is also determined by the expected growth of global output. Clarida et al. (2002) (henceforth, CGG) and Galì and Monacelli (2005) show that the domestic potential output itself is a function of the expected growth of domestic total factor productivity (TFP) and of the expected growth of output abroad. Hence, in a small open economy the NRI is mainly influenced by two components: a local component (the expected growth of domestic TFP) and a global component (the expected growth of global output).

As these two components of the NRI are unobservable we need to produce estimates of them and through these to estimate the NRI. One possibility is to specify a new Keynesian model and to use the Kalman filter method to estimate the various unobservable variables including the NRI (e.g., Laubach and Williams, 2003; Holston et al., 2016; Wynne and Zhang, 2017).[3] A second possibility is to use proxies for the unobservable variables and to estimate a single equation, possibly by the generalized method of moments (GMM).[4] Here we choose the second possibility. We use proxies

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[1] Those variables are model-dependent.
[2] See, e.g., Clarida et al. (1999) and Woodford (1999, 2001).
[3] Laubach and Williams (2003) and Holston et al. (2016), among many others, estimate a long-term NRI; the rate that is expected to prevail in the next few years after transitory shocks abate. By contrast, and similar to Barsky et al. (2014) and Curdia et al. (2015), we estimate a short-term NRI (the current rate that is affected by the transitory shocks) which we believe to be more relevant to the monetary policy rule.
[4] See, e.g., Clarida et al. (1998, 2000).

for expected local productivity growth and expected world growth and estimate an augmented Taylor rule (a single equation) for Israel for the period[5] 1995.1 to 2015.3. In addition to the above variables, we assume that the policy interest rate also reacts to the inflation gap[6] (the deviation of inflation from its target), the output gap, and the real exchange rate gap.

We find that the estimate of the NRI in Israel has been quite volatile, with a temporary but significant decline during the eruption of the global economic crisis in 2008–2009. This large decline was mainly due to the global factor, that is, the large decline in expected global growth. For the period 2011 to 2015 we do not observe a clear decline in the NRI relative to the period prior to 2008, contrary to the results in other studies worldwide.[7]

In order to highlight the advantage of using the available theory-based proxies for the NRI we do the following exercise. We use the estimated parameters to perform a dynamic projection of the level of the monetary interest rate for the period 2003.1 to 2015.3. We find that such an exercise projects very well the increase in the monetary interest rate in 2005–2007, the large decline in 2008–2009, and the temporary increase in 2010–2011. This is in contrast to the forecast achieved by using a naïve constant NRI, which fails to predict the dynamics of the monetary interest rate in 2005–2011. Hence, taking into account the effect of global growth on the NRI and the Solow residual as a proxy for TFP improves our understanding of the behavior of the monetary interest rate. We find that an estimate of the NRI that is based on the forward rate has lower explanatory power than our theory-based proxy for the NRI.

The rest of the paper is organized as follows. Section 2 presents the specification of the augmented Taylor-type rule and its justifications in the literature. Section 3

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[5] We ended the sample at 2015.3 because from 2015.3 onwards the Monetary Committee held the monetary interest rate constant at 0.1 percentage points, despite a prolonged period of negative inflation gap.
[6] We also show alternatives to the expected inflation gap.
[7] Holston et al. (2016) find that the NRI dropped in the past 25 years and, in particular, that it is at a historically low level in the U.S., the Euro area, and Canada. For the UK their NRI estimate dropped and stayed at the historically low level that was recorded in 1985. Similarly, Barsky et al. (2014) find that the U.S. NRI (estimate) dropped during the 2008 financial economic crisis to near its low levels in the previous two recessions but, in contrast to these recessions, it has stayed low since. Curdia et al. (2015) also find that the U.S. NRI dropped to a historically low level during the last crisis but, similar to our estimate for Israel, it increased significantly in the preceding year. Although Holston et al. (2016) do not include global growth as a factor in their model, they find evidence for a substantial co-movement in the estimates of the natural rates across the four economies, suggesting *"a great deal of interdependence in natural rates across economies"*.

presents and discusses the estimation and the empirical results. Section 4 performs some robustness checks and Section 5 concludes.

2. The Augmented Taylor-type Rule

This section presents the theoretical and empirical grounds for the estimated augmented Taylor-type rule (henceforth, ATR).

2.1. The classic Taylor rule

The classic Taylor (1993) rule is given by

$$i_t = \pi_t^T + r + \tau_\pi(\pi_t - \pi_t^T) + \tau_y \tilde{y}_t, \tag{1}$$

where i_t is the monetary interest rate, r is a constant equilibrium real rate, π_t is the rate of inflation, π_t^T is the inflation target, $\tilde{y}_t$ is the output gap, and τ_π and τ_y are positive coefficients. Taylor (1993) assumes (for the United States) that r and π_t^T are constant at 2 percentage points each. The coefficient of the inflation gap, τ_π, equals[8] 1.5 and the coefficient of the output gap, τ_y, equals[9] 0.5. The first augmentation of the Taylor rule refers to the equilibrium real rate, i.e., the natural rate of interest.

2.2. The natural rate of interest

Clarida et al. (1999) and Woodford (1999, 2001) show within the basic new Keynesian model that the theoretically optimal (desired) interest rate responds to a time-varying natural rate of interest (NRI) and the deviation of the (expected) inflation rate from its target. The NRI is defined as the real interest rate that would have prevailed in the absence of nominal rigidities (i.e., under flexible prices and wages).

In the basic new Keynesian model Woodford (2003) shows that the NRI is determined by the degree of households' impatience to consume and the expected growth of potential output.[10] For an open economy CGG (2002) show that the NRI is also affected by the expected growth of output abroad and that domestic potential output

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[8] A necessary condition for determinacy in the new Keynesian model is that $\tau_\pi > 1$, a condition known as the "Taylor principle."
[9] In Taylor (1999) τ_y equals 1.
[10] Woodford includes two other factors that affect the NRI: shocks to preferences and shocks to government consumption.

itself is a function of the expected growth of output abroad and the expected domestic total factor productivity (TFP). Specifically, they show that the log deviation of the NRI ($\overline{rr}_t$) is given by

$$\overline{rr}_t = \sigma_o E_t\{\Delta\bar{y}_{t+1}\} + \kappa_o E_t\{\Delta y^*_{t+1}\}, \tag{2}$$

where $\bar{y}$ is the domestic natural level of output (i.e., the output that would have been obtained if prices were fully flexible) and y^* is the (actual) foreign output. The operator E_t denotes the mathematical unconditional expectation. The parameters σ_0 and κ_0 are deep structural parameters, where κ_0 is a function of, among other things, the economy's degree of openness, measured by the weight of imported consumption in the CPI. The domestic natural level of output $\bar{y}$ is given by (CGG, 2002, equation (48)):

$$\bar{y}_t = \kappa^{-1}[(1 + \phi)a_t - \kappa_o y^*_t], \tag{3}$$

where κ is the elasticity of marginal cost with respect to domestic output, ϕ is the Frisch elasticity of labor supply, and a_t is (the log of) TFP. If we insert equation (3) into equation (2) we can represent the NRI in terms of the expected changes of domestic TFP and the expected growth of output abroad:

$$\overline{rr}_t = \tau_a E_t\{\Delta a_{t+1}\} + \tau_* E_t\{\Delta y^*_{t+1}\}, \tag{4}$$

where $\tau_a \equiv \sigma_0 \kappa^{-1}(1 + \phi)$ and $\tau_* \equiv \kappa_o(1 - \sigma_0 \kappa^{-1}) = \kappa_o \phi / \kappa$. Following CGG (2002), $\tau_a > 0$. As for τ_*, CGG (2002) show that its sign depends on the inverse of the intertemporal elasticity of substitution in consumption, σ: it is positive for $\sigma > 1$ and negative for $0 < \sigma < 1$.

Note that CGG (2002) specify the model in log-deviation form. Thus, for the estimation we should add to equation (4) a constant term (τ_c) that represents the degree of impatience.[11] Plugging the time-varying real NRI (equation (4)) instead of the constant NRI into equation (1) yields the following equation for the monetary interest rate:

$$i_t = \pi^T_t + \tau_c + \tau_a E_t\{\Delta a_{t+1}\} + \tau_* E_t\{\Delta y^*_{t+1}\} + \tau_\pi(\pi_t - \pi^T_t) + \tau_y \tilde{y}_t. \tag{5}$$

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[11] If β is the discount factor in the Euler equation for consumption, then $\tau_c = -\log(\beta)$.

2.3. The real exchange rate gap

In (small) open economies the question of whether to include the exchange rate in the interest rate rule is frequently raised. The literature supports both views. Based on theoretical grounds Taylor (2001) and Galì and Monacelli (2005) argue for its exclusion, while Svensson (2000) and DePaoli (2009) support its inclusion. As for empirics, Adolfson et al. (2007) include the lagged deviation of the real exchange rate from its trend in the central bank reaction function. Lubik and Schorfheide (2007) obtain mixed results: the nominal depreciation rate is included in Canada's and England's central bank reaction function, but not in Australia's and New Zealand's.

In Israel the real exchange rate is considered an important variable by policy makers. In this light it seems reasonable to include also the real exchange rate gap (deviation of the real exchange rate from its trend), $\tilde{q}_t$, in the estimated rule and to test whether it is significant. To this end, the interest rate equation is given by

$$i_t^d = \pi_t^T + \tau_c + \tau_a E_t\{\Delta a_{t+1}\} + \tau_* E_t\{\Delta y_{t+1}^*\} + \tau_\pi(\pi_t - \pi_t^T) + \tau_y \tilde{y}_t + \tau_q \tilde{q}_t, \qquad (6)$$

where i_t^d refers to the desired interest rate, as explained in the next subsection.

2.4. Monetary interest rate inertia

In light of the observed tendency of policy makers to smooth interest rates, it is usually assumed that the actual rate, i_t, is adjusted gradually to the desired interest rate, i_t^d, in the following form:

$$i_t = \gamma i_t^d + (1 - \gamma)i_{t-1}. \qquad (7)$$

Note that equation (7) can also be written as

$$\Delta i_t = \gamma(i_t^d - i_{t-1}). \qquad (7a)$$

According to equation (7a) the change in the monetary interest rate partially corrects the gap between the desired rate and the previous setting of the monetary interest rate. Plugging the desired interest rate of equation (6) into equation (7a), and adding a white-noise residual, ε_t^i, yields

$$\Delta i_t = \gamma \begin{pmatrix} \pi_t^T + \tau_c + \tau_a E_t\{\Delta a_{t+1}\} + \tau_* E_t\{\Delta y_{t+1}^*\} \\ +\tau_\pi(\pi_t - \pi_t^T) + \tau_y \tilde{y}_t + \tau_q \tilde{q}_t - i_{t-1} \end{pmatrix} + \varepsilon_t^i, \tag{8}$$

which is the basic interest rate equation for the estimation.

3. Estimation

For the estimation of equation (8) we have to use available data or proxies for the unobservable variables. In the following paragraph we briefly describe the data and proxies that we use.

As a proxy for expected productivity ($E_t\{\Delta a_{t+1}\}$) we use estimates of the change in the Solow residual (one quarter ahead), assuming a Cobb–Douglas production function;[12] that is, we use estimates of Δa_{t+1} as a proxy for $E_t\{\Delta a_{t+1}\}$ (denoted by $\Delta \hat{a}_{t+1}$). As a proxy for the expected growth of global output ($E_t\{\Delta y_{t+1}^*\}$) we use survey data on the expected GDP growth (one quarter ahead) in the U.S.[13] (denoted by $\exp\_yf_{t,t+1}$). For the inflation variable we use the CPI inflation rate over the recent four quarters, that is, $\pi 4_t = (\pi_t + \pi_{t-1} + \pi_{t-2} + \pi_{t-3})/4$, where π_t is the quarterly inflation rate in annual terms. For the inflation target (π_t^T) we use available quarterly data on the inflation target. For the output gap ($\tilde{y}_t$) and for the real exchange rate gap ($\tilde{q}_t$) we use the percentage deviation from the Hodrick–Prescott (HP) filtered trend of the relevant variables. Preliminary trials reveals that the first lag of $\tilde{y}_t$ and of $\tilde{q}_t$ fits better than the current variables, and so we use $\tilde{y}_{t-1}$ and $\tilde{q}_{t-1}$ in the equation.

In terms of the data and proxies the estimated equation can be written as follows (a hat ($\wedge$) represents the estimate of the "true" parameter or variable):

$$\Delta i_t = \hat{\gamma} \begin{bmatrix} \pi_t^T + \hat{\tau}_c + \hat{\tau}_a \Delta \hat{a}_{t+1} + \hat{\tau}_* \exp\_yf_{t,t+1} \\ +\hat{\tau}_\pi(\pi 4_t - \pi_{t,t+4}^T) + \hat{\tau}_y \tilde{y}_{t-1} + \hat{\tau}_q \tilde{q}_{t-1} - i_{t-1} \end{bmatrix} + \varepsilon_t^i. \tag{9}$$

The three variables $\Delta \hat{a}_{t+1}$, $\exp\_yf_{t,t+1}$, and $\pi 4_t$ on the right-hand side of equation (9) are either endogenous and/or proxies; that is, they are measured with an error. Thus, in

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[12] We extract a_t from the following equation: $a_t = y_t - \alpha l_t - (1 - \alpha)k_t$, where y_t, l_t, and k_t stand for the natural log of GDP, total man hours, and capital stock in the business sector, respectively; the estimate of the labor share (α) is 0.67.

[13] These estimates are taken from the Survey of Professional Forecasters conducted by the Federal Reserve Bank of Philadelphia.

order to get consistent estimates we need to use instrumental variables. A "good" instrument should be correlated with the relevant explanatory variable and uncorrelated with the error term. If there is no autocorrelation in the error term, as we assume, lagged endogenous variables can serve as instruments.

We use as instruments the first four lags of each variable that appears in equation (9). An exception to this choice is $\pi 4_t$. As instruments for this variable we use the four lags of the actual quarterly inflation rate (that is, we use π_{t-1} up to π_{t-4} as instruments). We also include four lags of $\tilde{y}_t$ and of $\tilde{q}_t$ in the list of instruments. Thus the total group of instruments consists of a constant term, $\pi_t^T, \pi_{t,t+4}^T$, and four lags of the following variables: $\{\Delta \hat{a}_t, \exp_{y f_{t,t+1}}, \pi_t, \tilde{y}_t, \tilde{q}_t, i_t\}$.

To estimate equation (9) we use the generalized method of moments (GMM). We estimate the equation for the whole period (1995.1–2015.3) and for sub-periods, as detailed below. The results are presented in Table 1. The second column of the table presents the estimates for the whole period. As can be seen, in this column all the estimates have the right sign, reasonable magnitude, and all, except for the estimate of τ_a, are significant.[14] Note that the J-statistic is not significant (indeed, it is very far from being significant), which indicates that the proposed instruments are valid. The Q(4) statistic, which tests autocorrelation up to the fourth lag, is not significant either.[15]

As for the components of the theory-based NRI (henceforth, TbNRI), the t-value of $\hat{\tau}_a$ is above 1 and that of $\hat{\tau}_*$ is 5.5. The coefficient of annual inflation is highly significant (t-value of 6.4) and its value (2.662) is much greater than 1, a necessary condition for the stabilization of the rule (the Taylor principle). Note also that $\hat{\tau}_y$ and $\hat{\tau}_q$ are quite large and highly significant.

The estimation period contains the first three quarters of the year 2002. This is a special period in which the policy results in a very large deviation from any reasonable rule.[16] In the third column of Table 1 we present estimates of the equation for the period that excludes the first three quarters of 2002. Note that the explanatory power (adjusted R^2) of the equation only slightly increases, but now $\hat{\tau}_a$ becomes significant and we also note a big improvement in Q(4).

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[14] By "significant" we mean having a significance level of at least 5%.
[15] However, the p-value is 0.062, which is quite close to being significant. As we shall soon see, when we correct for 2002, the autocorrelation coefficient declines considerably.
[16] In the first quarter of 2002 Governor Klein announced a surprise cut of the monetary interest rate by 2 percentage points. This unexpected act, which took place for reasons that were not related to the course of inflation or the output gap, reflects a large deviation from any reasonable policy rule.

A big improvement of the equation can be achieved if we drop 1995–1998, the first years of the inflation stabilization period. The estimates for that period (1999.1–2015.3, excluding the first three quarters of 2002) are presented in column 4. Now the t-values of all the coefficients of the equation increase and the adjusted R^2 of the regression equation sharply increases to 0.633.

A further improvement of the equation can be achieved if we start the estimation in 2003 (column 5 of Table 1). Here $\hat{\tau}_a$ becomes insignificant but the t-value of all the other estimates increase and adjusted R^2 further increases to 0.756.

In contrast to the above estimates, which are based on an estimated TbNRI, the estimates reported in column 6 of Table 1 are based on a constant NRI. A comparison of columns 3 and 6 reveals that the estimates of the various parameters and the test statistics are quite similar in the two specifications. Of course, since we exclude relevant information,[17] the explanatory power of the equation is reduced. Note also that $\hat{\tau}_y$ decreases and $\hat{\tau}_q$ increases. A possible interpretation of this result is that deleting relevant variables from the equation causes a bias in the estimation of the effects of the other variables. A comparison of columns 3 and 6 of Table 1 highlights the main contribution of this research: the inclusion of the two variables that characterize a theory-based NRI in a small open economy significantly improves the fit of a Taylor-type rule.

Figure 1 presents the estimated TbNRI and the constant NRI (calculated from the estimates in columns 3 and 6 of Table 1, respectively). Note that the TbNRI is quite volatile: it increased above the constant NRI in 1998–2000, declined below it in 2001–2003, increased again to an average level much above the constant NRI in 2004–2006, and declined well below it in 2008–2009 (due to the global economic crisis). Nevertheless, the average value of the TbNRI in the sample is about 0.3 percentage points, quite close to the estimated value of the constant NRI of 0.7 percentage points ($\hat{\tau}_c$ in column 6). Moreover, Figure 1 implies that the TbNRI was volatile around a constant trend between 1996 and 2015, with sharp temporary decreases in 2001–2003 and 2008–2009. For the period 2011 to 2015 we do not observe a clear decline in the NRI relative to the period prior to 2008. This result is in contrast to other empirical findings on a downward trend in the NRI in other countries; see, e.g., Wynne and Zhang (2017) and Holston et al. (2016).

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[17]We exclude significant variables from the equation.
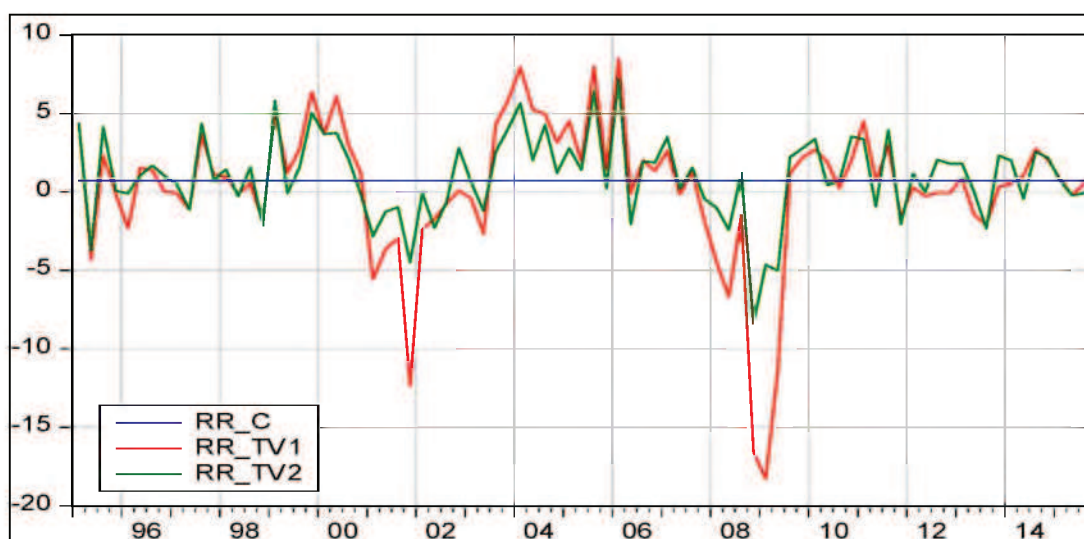
Figure 1: Estimated NRIs

Fig. 1: Three estimated natural rates of interest (NRIs) extracted from the augmented Taylor-type rule (equation (9)): a constant NRI, denoted by RR_C (blue line), a time-varying NRI in a rule that responds to current inflation, denoted by RR_TV1 (red line), and a time-varying NRI in a rule that responds to inflation expectations, denoted by RR_TV2 (green line).

Table 1: **GMM estimation of the augmented Taylor-type rule (equation (9)) for the period 1995.1–2015.3 and for sub-periods** (t-value in parentheses)

(1) Parameters	(2) 1995.1-2015.3 (N=83) Theory-based NRI	(3) 1995.1-2001.4 2002.4-2016.2 (N=80) Theory-based NRI	(4) 1999.1-2001.4 2002.4-2016.2 (N=64) Theory-based NRI	(5) 2003.1-2015.3 (N=51) Theory-based NRI	(6) 1995.1-2001.4 2002.4-2015.3 (N=80) Constant NRI
γ	0.096** (7.1)	0.092** (7.3)	0.089** (11.1)	0.083** (14.3)	0.085** (8.1)
τ_{const}	-6.437** (-4.0)	-6.387** (-4.0)	-5.522** (-4.5)	-7.887** (-10.5)	0.726 (1.2)
τ_a	0.532 (1.2)	0.735* (2.2)	0.564** (3.8)	0.017 (0.1)	
τ_*	3.087** (5.5)	2.814** (5.1)	2.294** (5.5)	3.339** (12.0)	
τ_π	2.662** (6.4)	2.204** (5.6)	2.203** (8.5)	2.835** (12.1)	1.966** (5.3)
τ_y	0.858** (4.5)	0.917** (4.4)	0.921** (8.8)	0.589** (4.8)	0.504** (3.0)
τ_q	0.424** (3.4)	0.305** (2.8)	0.352** (3.7)	0.309** (4.1)	0.528** (3.3)
Adjusted R^2	0.415	0.426	0.633	0.756	0.286
DW	1.96	1.93	2.026	2.34	1.70
Q(4) P-value(Q)	9.0 0.062	4.7 0.318	4.8 0.307	6.9 0.142	6.6 0.159
J-statistic P-value(J)	16.9 0.661	16.0 0.719	14.0 0.833	11.5 0.931	9.5 0.801

* and ** indicate statistical significance at the 5 percent and 1 percent level, respectively.

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On average, the estimates of the TbNRI and of the constant NRI are close. In order to highlight the importance of specifying a TbNRI, the ability of equation (9) to project the level of the monetary interest rate for the period 2003.1 to 2015.3 is compared with that of the naïve constant NRI equation. Figure 2 reports the results of this exercise. As can be seen, both specifications capture very well the decline in the monetary interest rate from 2003 to 2005. However, from 2006 to 2011 the naïve specification (the constant NRI) fails to capture the behavior of the monetary interest rate. On the other hand, the specification with the time-varying TbNRI continues to capture the dynamics of the monetary interest rate. It captures well the increase and decline in 2006–2007 and it captures remarkably well the dramatic decline in 2008–2009. It also captures the temporary increase in the interest rate in 2010–2011.

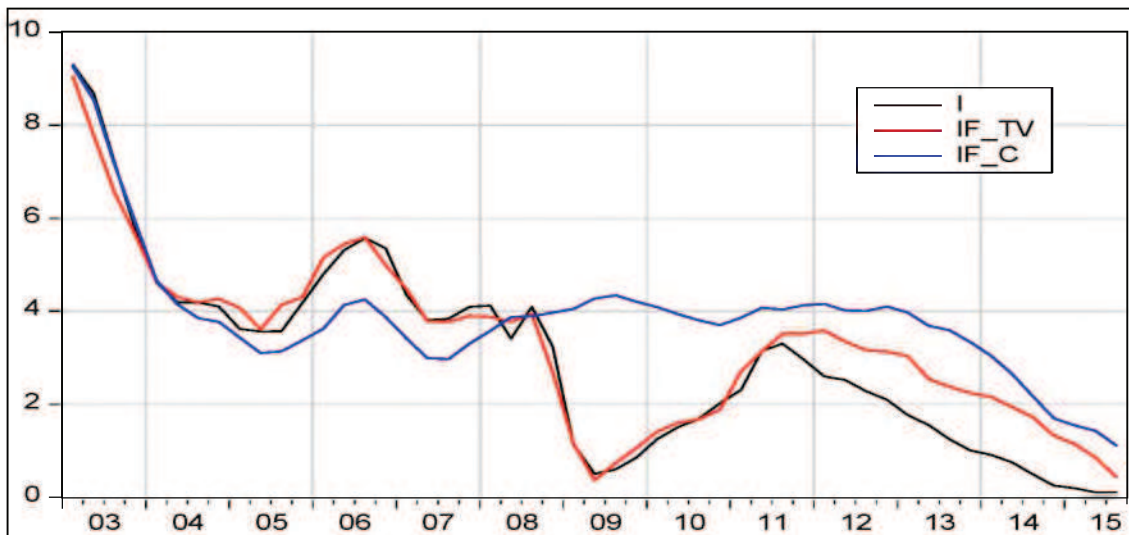**Figure 2: Actual and projected monetary interest rate for 2003.1 to 2015.3**

Fig. 2: Actual Bank of Israel monetary interest rate, denoted by I (black line), and projected monetary interest rate by a dynamic simulation of equation (9) with a constant NRI, denoted by IF_C (blue line), and with a time-varying NRI, denoted by IF_TV (red line).

By contrast, the projection under the assumption of a constant NRI fails to capture the decline in the monetary interest rate in 2008–2009. The reason is that apart from global growth, all the other variables in the augmented Taylor-type rule (which are local factors) cannot account for the large decline in the monetary interest rate, since the Israeli economy was not directly affected by the global economic crisis. Thus, only when we take into account the large and exceptional decline in global growth can we explain the drastic decline in the monetary interest rate. In the specification with the

TbNRI, the expected decline in global activity reduced the NRI and hence the monetary interest rate.

The projection exercise described above highlights the important informational content in the expected growth of world output for the NRI. By taking into account the effect of global growth on the NRI we can improve our understanding of the behavior of the monetary interest rate, especially in periods of drastic large-scale changes in the economic environment.

Nevertheless, from 2012 onwards we observe a large and persistent gap between the projected and actual rates. A close look at the results reveals that the model fails to capture the decline in the actual rate in the beginning of 2012. This is reflected in the persistent gap in the dynamic simulation, but is absent in the static simulation. We interpret this gap as an overestimate of the natural rate of interest, and assume that the Bank of Israel set its policy according to the "true" lower natural rate of interest. What exactly happened in the beginning of 2012 is an interesting subject but it is beyond the scope of the present study. One possible explanation is the different economic developments in the U.S. versus the Euro area, the two main trading partners of Israel. This different behavior is absent from our proxy for expected world growth, which reflects only expected growth in the U.S. Another possible explanation is the shift from an interest rate decided solely by a governor to one decided by a monetary committee (from October 2011 onward).

The next section presents robustness checks of the augmented Taylor-type rule (equation (9)) with respect to actual versus expected inflation, and with respect to the use of the implied forward rate as an alternative measure of the NRI.

4. Robustness Analysis

4.1 Actual inflation versus expected inflation as components of the inflation gap

In the specification of the interest rate rule in equation (9), the inflation gap is specified in terms of actual inflation in the previous year. Another possibility is to specify the rule in terms of expected inflation (i.e., to assume "inflation forecast targeting").[18]

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[18] See, e.g., Clarida et al. (2000).

Figure 3 presents the development of actual inflation in the previous four quarters and of expected inflation for the following four quarters.[19] As can be seen, actual inflation is much more volatile than expected inflation, as expected. An exception is the period 2008–2009, when there was a sharp decline in expected inflation but only a moderate decline in actual inflation. Of course, the question of which variable the policy is responding to, whether to actual inflation or expected inflation, may have implications for our estimate of the contribution of the NRI to the decline in the monetary interest rate in 2008–2009.

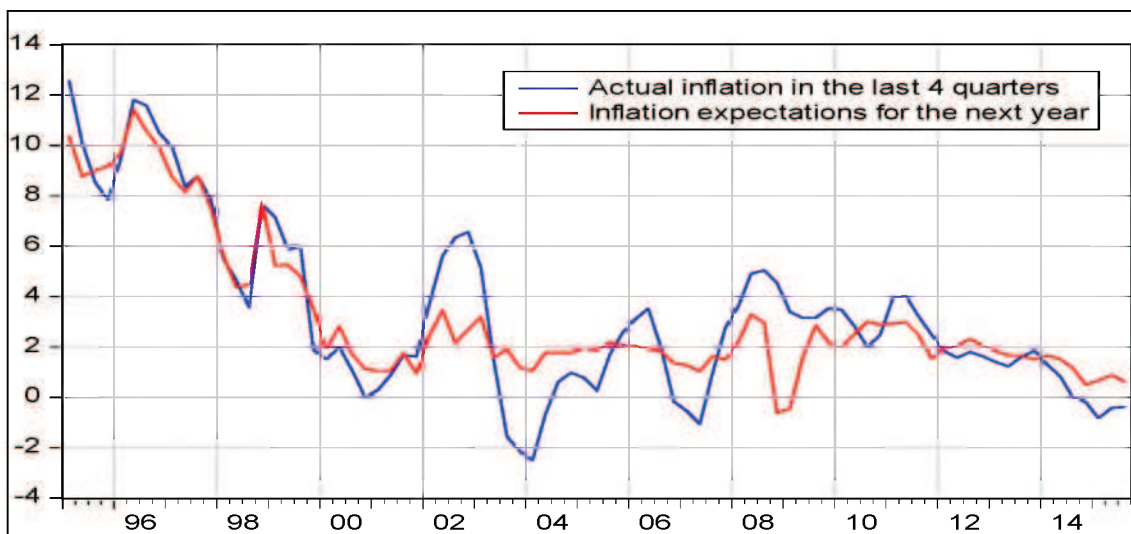**Figure 3: Actual and expected inflation for 1995.2 to 2015.3**

Fig. 3: Actual inflation rate in the last four quarters (blue line) and break-even inflation expectations in the following four quarters (red line).

In column 3 of Table 2 we present estimates of equation (9), where we replace actual inflation with the above-mentioned measure of expected inflation (column 2 repeats the estimates in column 3 of Table 1, under current inflation).[20] As can be seen, the estimate of τ_π is almost twice as large when it is attached to expected inflation, and the estimate of τ_* is much smaller. That is, when we use expected inflation the effect of the inflation gap increases while the effect of the global component is reduced. Note however that

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[19] We use market-based inflation expectations for four quarters ahead (break-even inflation derived from the Israeli bond market).

[20] Since there are three overlapping periods in $exp\_\pi_{t,t+4}$ and $exp\_\pi_{t-1,t+3}$, one suspects that $exp\_\pi_{t-1,t+3}$ is correlated with the error term (and the same holds for any lag up to the fourth). This correlation is due to possible errors in $exp\_\pi_{t,t+4}$, which serves as an estimate of the "true" expectations. Because of this we did not use lags of $exp\_\pi_{t,t+4}$ as instruments (we continued to include the first four lags of quarterly inflation as in the list of instrumental variables).

the adjusted R^2 declines from 0.415 to 0.342 and thus actual inflation is still an important variable and one to which the policy responds.

In Figure 1 we also present the TbNRI estimated when we use expected inflation (the green line). We can see that the two estimates of the TbNRI show similar behavior apart from two periods in which there was a big change in world growth, namely, the years 2001 and 2008–2009. In 2008–2009 the TbNRI under actual inflation reached a level of -18.3 percentage points. Under the expected inflation it declined to "only" -8.3 percentage points.[21] Thus, we can conclude that global growth contributed significantly to the sharp interest rate cut in the global economic crisis in 2008–2009.

Table 2: Robustness analysis. GMM estimation of equation (9) with alternative measures of the inflation gap and the NRI. Period: 1995.1–2001.4, 2002.4–2015.3 (N=80) (t-value in parentheses)

(1) Parameters	(2) Theory-based NRI	(3) Theory-based NRI	(4) Implied forward ($v105$) as proxy for NRI	(5) Theory-based NRI+implied forward
	Actual inflation	Expected inflation	Actual inflation	Actual inflation
γ	0.092**	0.0822**	0.118**	0.139**
	(7.3)	(6.4)	(5.7)	(5.4)
τ_{const}	-6.387**	-1.797	-1.635	-8.061**
	(-4.0)	(-1.3)	(-0.8)	(-6.7)
τ_{v105}			0.738	1.163**
			(1.5)	(3.2)
τ_a	0.735*	0.984*		0.255
	(2.2)	(2.3)		(1.5)
τ_*	2.814**	1.109**		2.051**
	(5.1)	(2.7)		(5.0)
τ_π	2.204**	4.816**	1.366**	1.560**
	(5.6)	(5.1)	(4.0)	(4.4)
τ_y	0.917**	1.003**	0.408**	0.686**
	(4.4)	(4.5)	(3.6)	(4.0)
τ_q	0.305**	0.146	0.397**	0.202**
	(2.8)	(0.8)	(3.4)	(3.0)
Adjusted R^2	0.415	0.342	0.292	0.509
DW	1.93	1.80	1.68	1.91
Q(4) P-value(Q)	4.7 0.318	2.5 0.632	6.4 0.170	5.4 0.246
J-statistic P-value(J)	16.0 0.719	15.3 0.756	10.5 0.880	18.4 0.755

* and ** indicate statistical significance at the 5 percent and 1 percent level, respectively.

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[21] We should note that our estimates are similar in magnitude to NRI estimates in the U.S. For example, the NRI in Barsky et al. (2014) dropped to about -6 percentage points since 2008, and in Curdia et al. (2015) it dropped to about -10 percentage points during the financial crisis.

4.2. Theory-based NRI versus implied forward rate as an alternative measure of the NRI

Several authors have used the implied forward rate as a proxy for the NRI.[22] Clarida (2009) suggests the forward rate from 5 to 10 years ahead as a proxy for the NRI on the grounds that the influence of business cycles and of monetary policy may not be reflected in that horizon's expectations. Similarly, Ilek and Binstock (2010) show that for the Israeli economy the forward rate from 3 to 10 years ahead is exogenous to the monetary interest rate.

From a theoretical point of view the NRI is indeed exogenous to the monetary interest rate, but it is also a function of both current and short-term expected shocks, as reflected in equation (6). Hence, while the forward interest rate may be a good proxy for the long-run NRI (à la Laubach and Williams), it is not a good proxy for the short-run NRI, which is the relevant variable for setting the monetary interest rate. Another problem in using the forward rate as a proxy for the NRI is that it includes a term premium that may be time-varying.

In any case, we also estimate equation (9) using the implied forward rate from 5 to 10 years ahead (denoted by $v105$). The results are shown in column 4 of Table[23] 2. As can be seen, the t-value of the coefficient of the implied forward rate is 1.5 and the adjusted R^2 of the equation declines from 0.415 (column 2) to 0.292 (column 4). From this it appears that the contribution of the implied forward rate to the behavior of the NRI (and through it to the behavior of the monetary interest rate) is much lower than that of the TbNRI. Furthermore, when we look at the figures of the estimated TbNRI and the NRI derived from the implied forward rate, we can clearly see that the forward rate cannot account even partly for the dramatic decline in the monetary interest rate in 2008–2009 (Figure 4).

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[22] See, e.g., Bomfim (2001), Clarida (2009), and Pasenti (2009). For an application to Israel see Elkayam (2001), Ilek and Binstock (2010), and Argov et al. (2012).
[23] In column 2 we assume that the NRI is $NRI\_a_t = \tau_c + \tau_a E_t\{\Delta a_{t+1}\} + \tau_* E_t\{\Delta y^*_{t+1}\}$, while in column 4 we assume that it is $NRI\_b_t = \tau_c + \tau_{v105} v105_t$.

Figure 4: Estimated TbNRI, and estimated NRI derived from the implied forward rate
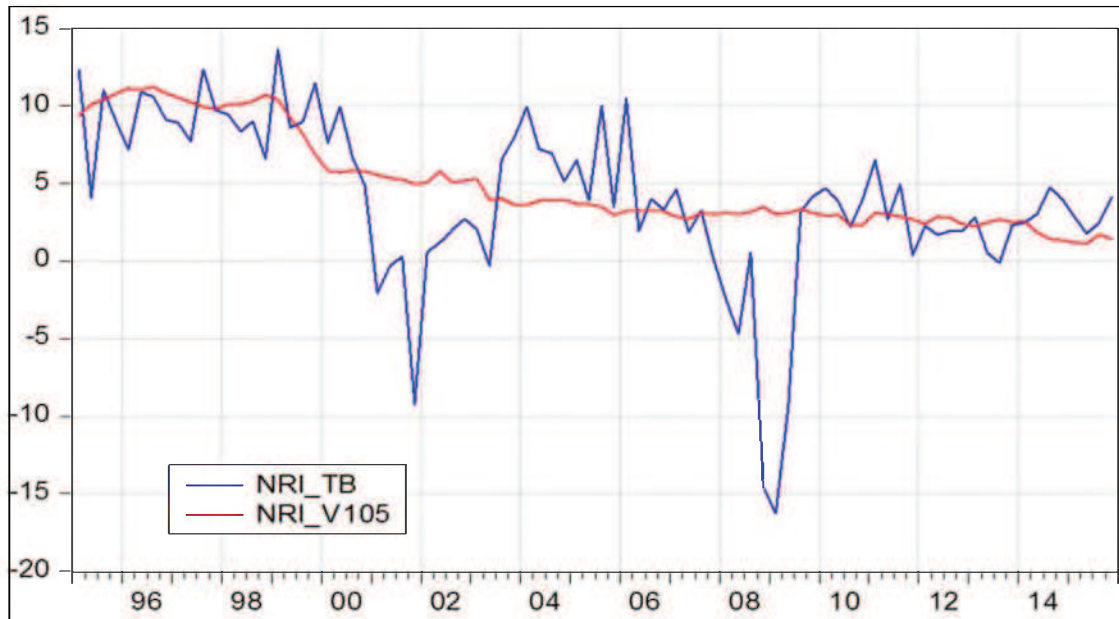

Fig. 4: Estimated TbNRI derived from the estimates in column 2 in Table 2 (blue line), and estimated NRI derived from the implied forward rate, based on the estimates in column 4 in Table 2 (red line).

Column 5 of Table 2 presents the estimates of equation (9), where the implied forward rate is added to the equation, alongside the other components of the TbNRI. As can be seen, the coefficient on that variable becomes significant. This result suggests that the forward rate might contain some relevant information that is not captured by the other two components of the NRI.

5. Conclusions

We estimate an augmented Taylor-type rule for Israel that includes, beyond the inflation gap, the output gap, and the exchange rate gap, also the expected global growth and a domestic proxy for productivity as a proxy for the theory-based natural rate of interest (TbNRI) in an open economy.

We find that the expected global growth had a meaningful effect on the natural rate of interest in Israel, and through it on the monetary interest rate. In particular, it accounts for a significant part of the drop in the monetary interest rate during the economic crisis in 2008–2009, and it also explains well the cyclical dynamics of the monetary interest rate in 2006–2007 and 2008–2011. Furthermore, we do not observe a clear decline in the Israeli TbNRI relative to the period prior to 2008, contrary to the

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results in other studies worldwide, although our estimate during the crisis resembles estimates for the U.S.

We find that while the forward interest rate may be a good proxy for the long-term NRI (à la Laubach and Williams), it is not a good proxy for the short-term NRI, which is the relevant variable for setting the monetary interest rate. In particular, our estimate of the NRI that is based on the forward interest rate does not account for the monetary interest rate dynamics in 2006–2007 and 2008–2011.

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