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**WORKING PAPER SERIES**

**NO. 500 / JULY 2005**

**FLESHING OUT THE  
MONETARY TRANSMISSION  
MECHANISM**

**OUTPUT COMPOSITION  
AND THE ROLE OF  
FINANCIAL FRICTIONS**

by André Meier  
and Gernot J. Müller

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# FLESHING OUT THE MONETARY TRANSMISSION MECHANISM

# OUTPUT COMPOSITION AND THE ROLE OF FINANCIAL FRICTIONS <sup>1</sup>

by André Meier <sup>2</sup>  
and Gernot J. Müller <sup>3</sup>

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## Abstract

Financial frictions affect the way in which different components of GDP respond to a monetary policy shock. We embed the financial accelerator of Bernanke, Gertler and Gilchrist (1999) into a medium-scale Dynamic General Equilibrium model and evaluate the relative importance of financial frictions in explaining monetary transmission. Specifically, we match the impulse responses generated by the model with empirical impulse response functions obtained from a vector autoregression on US time series data. This allows us to provide estimates for the structural parameters of our model and judge the relevance of different model features. In addition, we propose a set of simple and instructive specification tests that can be used to assess the relative fit of various restricted models. Although our point estimates suggest some role for financial accelerator effects, they are actually of minor importance for the descriptive success of the model.

*JEL classification:* E32, E44, E51

*Keywords:* Monetary Policy, Output Composition, Financial Frictions, Minimum Distance Estimation

## Non-technical Summary

The last two decades have seen a tremendous body of work attempting to characterize empirically the transmission of monetary policy shocks based on structural Vector Autoregressions (VAR). Although there is now a fair consensus on the basic pattern of the economy's response to a monetary policy shock, the precise channels of transmission and their relative importance have remained a topic of debate. In particular, it is largely unclear whether or not there is a significant channel of transmission above and beyond the classical interest rate channel. One serious candidate is provided by the literature on financial frictions. In fact, imperfect information in loan markets can make borrowing conditions a function of borrowers' net worth, giving rise to a "balance sheet channel" that tends to reinforce the impact of a given monetary shock. A formal model of such a "financial accelerator" was provided by Bernanke, Gertler and Gilchrist (1999). Despite some suggestive evidence, however, the quantitative relevance of this feature is still an open question.

In the present paper, we thus focus on the role of financial frictions for the responses of key macroeconomic variables to a monetary policy shock. Specifically, we start from the VAR-based evidence and relate it to the predictions of a Dynamic Stochastic General Equilibrium (DSGE) model with nominal rigidities. Our model encompasses several features that are commonly considered in the literature but additionally allows for financial frictions. We take this structural model to the data using a minimum distance strategy similar to Rotemberg and Woodford (1997) and Christiano, Eichenbaum and Evans (2005). Given that economic interest centrally bears on the impulse responses associated with a monetary policy shock, it is natural to consider this statistic as the critical nexus between theory and data. Consequently, we obtain estimates for the structural parameters of our model by matching the impulse response functions estimated from US data (1980:1 - 2003:4) with those implied by the model.

The different features of our model, including financial frictions, have distinct implications for the behavior of individual output components. Therefore, our analysis considers not only aggregate output but also looks at the specific responses of consumption and investment, along with inflation, the real wage and the short-term interest rate. Moreover, we explicitly take correlation between different impulse responses into account by using an efficient weighting scheme in our minimization. Apart from promising more precise estimates, this approach also lends itself nicely to comparative model evaluation. Specifically, we conduct distance metric tests to examine the relative fit of several restricted models that are nested in the most general specification. This provides us with direct evidence on which features are quantitatively important to account for the stylized facts of monetary transmission.

Our model, evaluated at the parameter estimates, is able to reproduce quite well the shape

and magnitude of the empirical impulse responses. For this to be the case, the model requires strong nominal rigidities in prices and slightly less so in wages. There is also evidence in favor of price indexation and against strong habit formation in consumption. In addition, our estimates ascribe an important role to capital adjustment costs - apparently an indispensable feature on the real side of the model. Interestingly, the financial accelerator itself appears to be of lesser importance. Although we obtain sizeable point estimates for the relevant parameter, these estimates fail to be statistically significant throughout. The same conclusion is suggested by our distance metric tests, which show financial frictions to have only a marginal impact on improving the model's fit with the data. In a sense, this finding may lend support to the widespread use of DSGE models that refrain from incorporating financial accelerator effects. An obvious caveat is that we focus on the propagation of one shock only, thus singling out monetary transmission as the relevant benchmark of empirical success. It is therefore conceivable that financial frictions have a more crucial role to play as the model is confronted with additional aspects of the data.

# 1 Introduction

The last two decades have seen a tremendous body of work attempting to characterize empirically the transmission of monetary policy shocks based on structural Vector Autoregressions (VAR). In light of the contributions by Christiano, Eichenbaum and Evans (1999), Woodford (2003) and others, it seems fair to speak of an emerging consensus on the basic pattern of the economy's response to a monetary policy shock. Nonetheless, the precise channels of transmission and their relative importance have remained a topic of debate. In particular, it is largely unclear whether or not there is a significant channel of transmission above and beyond the classical interest rate channel. One serious candidate is provided by the literature on financial frictions. In fact, imperfect information in loan markets can make borrowing conditions a function of borrowers' net worth, giving rise to a "balance sheet channel" that tends to reinforce the impact of a given monetary shock. A formal model of such a "financial accelerator" was provided by Bernanke, Gertler and Gilchrist (1999), henceforth BGG. Despite some suggestive evidence, however, the quantitative relevance of this feature is still an open question.

In the present paper, we thus focus on the role of financial frictions for the responses of output, consumption and investment to a monetary policy shock. Specifically, we start from the VAR-based evidence and relate it to the predictions of a Dynamic Stochastic General Equilibrium (DSGE) model with nominal rigidities. Our model encompasses several features that are commonly considered in the literature but additionally allows for financial frictions in line with BGG. We take this model to the data using a minimum distance strategy similar to Rotemberg and Woodford (1997) and Christiano, Eichenbaum and Evans (2005), henceforth CEE.

Our motivation is twofold. First, given the profession's interest to work with empirically successful yet parsimonious models, it is a critical task to establish the relative importance of different features on the real side and on the nominal side of New Keynesian models. For an example of the latter, consider the challenge of establishing whether nominal rigidities are more relevant in wage setting or in price setting, as has been investigated, for example, by CEE. On the real side, the financial accelerator is but one of the features that should be examined more thoroughly. As Woodford (2003, p.11) puts it, "there is no substitute for careful empirical research to flesh out the details of a quantitatively realistic account of the monetary transmission mechanism." Second, better insights into the nature of monetary transmission have obvious benefits for policy-making. In this context, the microfoundations of the financial sector may seem of particularly topical importance insofar as the new Basle Capital Accord is expected to affect the sensitivity of financing costs with respect to the borrower's balance sheet quality.

Given that economic interest centrally bears on the impulse responses associated with a monetary policy shock, it is natural to consider this statistic as the critical nexus between

theory and data. Consequently, we seek to obtain estimates for the structural parameters of our model by matching the impulse response functions estimated from US data (1980:1 - 2003:4) with those implied by the model.

The idea of estimating a DSGE model with a minimum distance approach goes back to Rotemberg and Woodford (1997).<sup>1</sup> Their small-scale New Keynesian model included only output, inflation and the nominal interest rate. The model was subsequently extended by Amato and Laubach (2003), who also included wage inflation; Boivin and Giannoni (2003), who allowed for the indexation of prices; and Giannoni and Woodford (2003), who combined both assumptions. CEE use a medium-scale model that incorporates price and wage rigidities and also allows for a richer specification of the real side of the economy, taking investment and capital utilization into account.

In contrast to CEE, we highlight the possible role of financial frictions in the transmission of monetary policy shocks. In doing so, we rely on the theoretical work of BGG who introduced a financial accelerator into the DSGE framework. Because financial frictions have distinct implications for the behavior of individual output components, our analysis considers not only aggregate output, as has been common practice in the literature, but also looks at the specific responses of consumption and investment. Indeed, compositional effects are likely to contain important information on the nature of monetary transmission, as has also been argued in a recent paper by Angeloni et al. (2003). These authors note striking compositional differences in the impulse responses for US and EU area data that cannot be fully explained by the structural features of prominent DSGE models. However, the models considered by Angeloni et al. (2003), i.e. CEE and Smets and Wouters (2003), do not feature the sort of financial accelerator effects we are set to study.

Christiano, Motto and Rostagno (2003), in another related paper, account for financial frictions in analyzing the origins of the Great Depression. Overall, their model performs well and replicates several key features of the historical data. However, the paper does not isolate the precise contribution of financial frictions to the transmission of a given shock, although the authors emphasize that this would provide crucial information for future model development. Our own paper attempts to provide this additional insight with respect to the transmission of monetary policy shocks.

Lastly, our econometric approach aims to extend the work of Rotemberg and Woodford and CEE by using a different, more efficient weighting scheme. This addresses the criticism by Schorfheide (2003) that previous examples of minimum distance estimation have not sufficiently

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<sup>1</sup>Some alternative ways of estimating DSGE models have been put forward recently. Altig et al. (2005) extend the methodology of CEE, using several shocks instead of relying on the monetary policy shock only. Full-information techniques have also been suggested. Ireland (2004), for instance, uses classical maximum likelihood methods to estimate a New Keynesian model, while Smets and Wouters (2004) apply Bayesian methods.

taken into account dependencies between impulse responses across periods and series. Apart from promising more precise estimates, our approach also lends itself nicely to comparative model evaluation. Specifically, we provide distance metric tests to examine the relative fit of several restricted models which are nested in our most general specification.

The remainder of this paper is structured as follows. In section 2, we introduce the details of our model, i.e. the stylized economy for which we compute theoretical impulse responses. Section 3 looks at the empirical counterpart, presenting our data, our VAR model and the associated impulse responses. Section 4 contains a detailed description of our estimation strategy. Our results are provided in section 5, and section 6 concludes. The discussion of less instructive technicalities as well as all tables and figures are relegated to the appendix.

## 2 The Model

The model we consider features a financial accelerator in the framework of a DSGE model with monopolistic competition and nominal rigidities. The way we model the financial accelerator largely follows BGG. However, to their exposition we add a few features that allow for richer dynamics of the model in response to a monetary policy shock. The model distinguishes households, entrepreneurs, retailers and a central bank, whose monetary policy is characterized by an interest feedback rule. Households are infinitely-lived and choose consumption intertemporally and intratemporally over differentiated goods provided by retailers. Our specification of preferences allows for internal habit formation in consumption as in Amato and Laubach (2004). Further, households provide differentiated labor services to entrepreneurs and set wages in a staggered fashion à la Calvo. Entrepreneurs hire labor and combine it with capital to produce wholesale output in a fully competitive environment. In order to introduce monopolistic competition in the goods market, the model comprises a retail sector. Retailers buy wholesale output from entrepreneurs and transform it into differentiated goods which are then sold on to households for consumption purposes and to the entrepreneur sector for the production of capital goods. Retailers face downward sloping demand functions and also set prices à la Calvo.

Before we describe the objectives and constraints of all agents in greater detail, the role of the entrepreneur sector should be highlighted. This sector is, in fact, the key for the working of the financial accelerator. Entrepreneurs are risk-neutral and have a finite horizon. Because entrepreneurs are different from households, the model does not collapse into a representative agent framework, so borrowing and lending is possible in equilibrium. Financial frictions arise from asymmetric information in the relationship between borrowers (i.e. entrepreneurs) and lenders (i.e. a financial intermediary who ultimately represents households and thus need not be modeled explicitly). Specifically, lenders are assumed to face positive costs in the case they decide

to audit a debtor's economic performance. To minimize resources lost in monitoring, lenders will only do this when the borrower declares himself unable to honor his contractual obligations, i.e. in a situation of (supposed) financial distress. Hence, auditing costs in the model should be interpreted as proxying for all kinds of expenses associated with debtor bankruptcy, such as accounting and legal expenses or losses arising from asset liquidation. These costs cause loans to be traded at a premium over the risk-free rate and give an important role to borrowers' balance sheet conditions. In particular, if entrepreneurial wealth is small with respect to the total amount of financing required, bankruptcy is more likely and expected default costs rise. As a consequence, borrowers must pay a relatively high premium in equilibrium to compensate lenders. This mechanism has interesting implications for the propagation of shocks and the cyclicity of investment, spending and output. Specifically, to the extent that a recession depresses entrepreneurial net worth, say by causing a decline in asset prices, it automatically triggers a rise in the external finance premium, too. The countercyclical behavior of the finance premium tends to amplify swings in borrowing and lead to deeper fluctuations of real activity. Likewise, monetary policy shocks have more pronounced effects in that interest rate hikes, which already create more precarious business conditions, simultaneously raise the risk premium. One of the goals of our paper is to rigorously assess the quantitative importance of this mechanism. To do so, we now turn to a more formal presentation.

## 2.1 Aggregation of Final Goods

Final goods  $Y_t$  - used for consumption and investment - are bundles of differentiated goods  $Y_t(z)$ ,  $z \in [0, 1]$ , which are provided by a continuum of monopolistically competitive retailers. The usual Dixit-Stiglitz aggregator reads as

$$Y_t = \left[ \int_0^1 Y_t(z)^{\frac{\epsilon-1}{\epsilon}} dz \right]^{\frac{\epsilon}{\epsilon-1}}. \quad (1)$$

The optimal allocation of expenditure across differentiated goods implies a downward sloping demand function for a generic good  $z$ ,

$$Y_t(z) = \left( \frac{P_t(z)}{P_t} \right)^{-\epsilon} Y_t, \quad (2)$$

where  $P_t(z)$  denotes the price of good  $Y_t(z)$  and  $\epsilon$  measures the price elasticity of demand among differentiated goods.  $P_t$  denotes the price index of final goods given by

$$P_t = \left[ \int_0^1 P_t(z)^{1-\epsilon} dz \right]^{\frac{1}{1-\epsilon}}. \quad (3)$$

## 2.2 Retailers

Retailers purchase wholesale output from entrepreneurs and transform it into differentiated goods using a linear technology. This has two implications. First, up to a first-order approxi-

mation, the amount of final goods varies one-for-one with the amount of wholesale goods in the economy. Second, nominal marginal costs in the retail sector are equal to the price of wholesale output,  $P_t^w$ .

Retailers set prices to maximize profits, but their ability to do so is constrained exogenously. Specifically, in a discrete time version of Calvo (1983), we assume that each retailer can reoptimize his price in a given period with probability  $1 - \theta_p$ , independently of other firms and of the time elapsed since the last adjustment. The law of large numbers implies that a fraction  $1 - \theta_p$  of retailers reoptimize their prices each period. During the intervals between reoptimizations, individual prices are partially indexed to lagged inflation, where  $\kappa_p$  governs the degree of indexation. Consequently, if the price for good  $z$  has not been reoptimized for  $k$  periods, it is given by  $P_{t+k}(z) = P_t(z) (P_{t+k-1}/P_{t-1})^{\kappa_p}$ . Indexation rules of this type have been suggested as a simple way to account for inertia in the observed inflation response to a monetary shock. In line with Rotemberg and Woodford (1997) and BGG, we also assume that price setting occurs prior to the realization of any aggregate time  $t$  disturbance. Therefore, if reoptimization is possible, a generic retailer  $z$  will set  $P_t^*$  in order to maximize

$$E_{t-1} \sum_{k=0}^{\infty} \left[ \theta_p^k \Delta_{t,k} \frac{P_t^* (P_{t+k-1}/P_{t-1})^{\kappa_p} - P_{t+k}^w Y_{t,t+k}(z)}{P_{t+k}} \right] \quad (4)$$

subject to the demand function (2).  $Y_{t,t+k}(z)$  denotes the sales of retailer  $z$  in period  $t+k$ , if the most recently optimized price came into effect in period  $t$ . Note that future profits are discounted at rate  $\theta_p^k \Delta_{t,k}$ , where  $\Delta_{t,k}$  stands for the intertemporal marginal rate of substitution of households, who own the retail firms. The factor  $\theta_p^k$  gives the probability that prices will not be reoptimized for  $k$  periods. The solution to the above maximization problem satisfies the first-order condition

$$E_{t-1} \left\{ \sum_{k=0}^{\infty} \theta_p^k \Delta_{t,k} Y_{t,t+k}(z) \left[ \frac{P_t^* (P_{t+k-1}/P_{t-1})^{\kappa_p}}{P_{t+k}} - \frac{\epsilon}{\epsilon-1} X_{t+k} \right] \right\} = 0, \quad (5)$$

where  $X_t = P_t^w/P_t$  denotes the relative price of wholesale output in terms of final output, our numeraire.  $X_t$  thus provides a measure for the real marginal costs facing retailers. If all retailers are able to reoptimize prices each period, i.e. if  $\theta_p = 0$ , prices are set to maintain a constant markup over expected nominal marginal costs: the optimality condition (5) simplifies to  $P_t^* = [\epsilon/(\epsilon-1)] E_{t-1} P_t^w$ . The size of the markup naturally depends on  $\epsilon$ , the price elasticity of demand among differentiated goods.

If instead  $0 < \theta_p < 1$ , log-linear approximations<sup>2</sup> of (5) and the aggregate price index (3) imply the following relationship between inflation, defined as  $\pi_t = \log(P_t/P_{t-1})$ , and real

<sup>2</sup>In the following, we rely on log-linear approximations around a non-stochastic steady state. Small letters are used to denote the log deviation of a variable from its steady-state value, e.g.  $x_t = \log(X_t/X)$ . Note that variables without time subscripts refer to steady-state values.



marginal costs  $x_t$ :

$$E_{t-1}(\pi_t - \kappa_p \pi_{t-1}) = \beta E_{t-1}(\pi_{t+1} - \kappa_p \pi_t) + \lambda_p E_{t-1} x_t, \quad (6)$$

where  $\lambda_p = (1 - \theta_p)(1 - \beta\theta_p)/\theta_p$ . Note that (6) is a variant of the New Keynesian Phillips Curve. Abstracting from the issue of indexation, inflation can be seen to respond both to expected future inflation and to pressures stemming from current marginal cost.

## 2.3 Entrepreneurs

The entrepreneur sector, in which the financial accelerator originates, is modeled largely as in BGG. Entrepreneurs hire labor and combine it with purchased capital to produce wholesale output. In contrast to retailers, they operate in a fully competitive environment. Entrepreneurs have a finite horizon, and a fraction  $1 - \iota$  exits business in each period. This assumption is meant to capture the phenomenon of ongoing births and deaths of firms. At the same time, it guarantees that entrepreneurs remain dependent on external funds. When they exit business, entrepreneurs' equity is transferred to households.<sup>3</sup>

### 2.3.1 Production

Wholesale goods are produced according to the technology  $Y_t^w = K_t^\alpha H_t^\Omega (H_t^e)^{1-\alpha-\Omega}$ , where  $K_t$  denotes the aggregate capital stock,  $H_t$  denotes aggregated labor services and  $H_t^e$  denotes entrepreneurial labor services (which are assumed to be constant and normalized to one). As in Erceg, Henderson and Levin (2000), aggregated labor services are a composite of differentiated labor services provided by individual households. The problem of the household as a monopolistic supplier of differentiated labor services is discussed below. A log-linear approximation of the production function is given by

$$y_t = \alpha k_t + \Omega h_t. \quad (7)$$

Entrepreneurs' demand for aggregate household labor services is obtained from equating the real marginal product of labor and the real wage,  $W^r$ . In log-linear terms, this condition reads as

$$y_t - h_t + x_t = w_t^r. \quad (8)$$

### 2.3.2 Investment dynamics

At the end of period  $t$ , entrepreneurs purchase capital that is used for production in  $t + 1$ . The demand for capital is affected by two types of frictions, namely capital adjustment costs

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<sup>3</sup>This assumption mimics the setup in Christiano, Motto and Rostagno (2003) and avoids introducing a distinct category of entrepreneurs' consumption as in BGG. Consequently, our model has the desirable property that consumption is solely governed by the intertemporal optimization of households and does not include a separate consumption term which would arise as an artifact of the heterogeneous agents setup.

and agency problems in the credit market. Regarding the former, we assume that the aggregate capital stock evolves according to  $K_{t+1} = \Phi(I_t/K_t) K_t + (1-\delta)K_t$ , where  $I_t$  represents aggregate investment and  $\delta$  denotes the depreciation rate.  $\Phi(\cdot)$  is an increasing and concave function capturing the presence of adjustment costs in the production of capital goods. We restrict this function so that the price of capital goods is unity in the steady state, i.e.  $\Phi'(I/K) = 1$ . Moreover,  $\Phi(I/K) = \delta$  in the steady state, so a log-linear approximation to the law of motion for capital reads as

$$k_{t+1} = \delta i_t + (1 - \delta)k_t. \quad (9)$$

Conceptually, it is convenient to think of investment as being carried out in a distinct and perfectly competitive capital-producing sector owned by entrepreneurs. Here, final goods,  $I_t$ , are combined with existing capital,  $K_t$ , and transformed into new capital,  $K_{t+1}$ , under the technological constraints given by the function  $\Phi(\cdot)$ . The new capital is then sold to entrepreneurs at the price (in terms of the numeraire good)  $Q_t$ . We assume that investment takes time to plan, so investment expenditure is set two periods in advance. Such a time span between planning and realizing investment expenditure seems highly plausible and is suggested, *inter alia*, by Christiano and Todd (1996). As a consequence, while the asset price  $Q_t$  adjusts immediately in response to shocks, the investment response is delayed. The first-order condition that determines the investment decision of capital producers is given by  $E_{t-2}Q_t = E_{t-2}[\Phi'(I_t/K_t)]^{-1}$ . A log-linear approximation of this condition reads as

$$E_{t-2}q_t = \varphi E_{t-2}(i_t - k_t), \quad (10)$$

where  $\varphi = (-\Phi''/\Phi')(I/K)$  measures the elasticity of the price of capital with respect to the investment-capital ratio. As emphasized in BGG, it is through the introduction of adjustment costs that volatile asset prices contribute to the fluctuations of entrepreneurial wealth. In addition, adjustment costs smooth out the investment response to a given shock. In the steady state, producing new capital does not yield any profits, because capital production exhibits constant returns to scale. Outside the steady state, however, profits from capital production may differ from zero, because the existing capital stock is predetermined and cannot be adjusted freely. Specifically, real profits are given by  $\Pi_{E,t} = Q_t\Phi(I_t/K_t)K_t - I_t$ .<sup>4</sup> These profits are added to the wealth of entrepreneurs.

### 2.3.3 Financial frictions

Entrepreneurial activity is exposed to an idiosyncratic shock,  $\omega_t > 0$ , which has a mean of one and affects multiplicatively the total payoff from the individual entrepreneur's business.

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<sup>4</sup>The effect of capital accumulation itself on adjustment costs is of second order and thus omitted here, see BGG.

Specifically, the total payoff in period  $t$  consists of  $\omega_t$  times the sum of production revenues accruing to capital and the market value of the remaining capital stock. In the aggregate, because  $E\omega_t = 1$ , this amounts to  $\alpha X_t Y_t + (1 - \delta) Q_t K_t$ .

Capital demand is determined by the expected marginal return to capital. The realized marginal return to capital is given by

$$R_t^k = (\alpha Y_t X_t / K_t + (1 - \delta) Q_t) / Q_{t-1}, \quad (11)$$

which implies, in log deviations,

$$r_t^k = \alpha \frac{Y X}{K R^k} (y_t + x_t - k_t) + \frac{1 - \delta}{R^k} q_t - q_{t-1}. \quad (12)$$

To the extent that capital purchases at the end of period  $t$ ,  $Q_t K_{t+1}$ , exceed entrepreneurial net worth,  $N_{t+1}$ , entrepreneurs depend on external finance, which is provided by a financial intermediary. This intermediary earns zero profits in equilibrium and can perfectly diversify the idiosyncratic risk associated with individual entrepreneurial projects. Opportunity costs are, therefore, given by the riskless interest rate,  $R_{t+1}$ , paid on real deposits with the intermediary from  $t$  to  $t + 1$ .

However, the relationship between borrowers and lenders is affected by asymmetric information with respect to the above-mentioned shock  $\omega_t$ . In particular, the intermediary does not observe realizations of  $\omega_t$  costlessly but faces monitoring costs equal to a fraction  $\mu$  of the entrepreneur's total payoff if he wants to learn about  $\omega_t$ . This assumption introduces costs of default into the model and drives a wedge between lenders' opportunity cost and the cost of credit facing entrepreneurs. BGG derive the optimal one-period loan contract under these circumstances and show that it links repayment to a threshold value  $\bar{\omega}_t$ . For any realization of the idiosyncratic shock above this value, the borrower pays the lender a fixed contractual amount, while for any realization below  $\bar{\omega}_t$ , the borrower defaults on his debt, so the lender audits the borrower and seizes all remaining assets net of monitoring costs. The interaction of risk-neutral entrepreneurs with a risk-averse financial intermediary also implies that, through the conditions of the loan contract, entrepreneurs bear all the aggregate risk. In the appendix, we detail the derivation of BGG's financial accelerator and show that the optimal contract implies an increasing relationship between the entrepreneurs' capital to net worth ratio and the premium on external funds. This relationship is the essential characteristic of the financial accelerator, since it relates financing conditions to the current balance sheet situation of borrowers. In log-linear terms,

$$E_t r_{t+1}^k - r_{t+1} = -\chi (n_{t+1} - q_t - k_{t+1}), \quad (13)$$

where  $\chi$  measures the elasticity of financing conditions with respect to the net worth to capital ratio, see equation (A8) in the appendix. Intuitively, the more severe the agency problem

between borrowers and lenders and, thus, the greater the extent of financial frictions in the economy, the higher  $\chi$  will be. This parameter will therefore play a key role in the discussion below.

Lastly, entrepreneurs' wealth remains to be properly defined. At the end of period  $t$ , entrepreneurial net worth,  $N_{t+1}$ , consists of the entrepreneurial equity  $V_t$  held by the fraction  $\iota$  of entrepreneurs who stay in business, the share earned by entrepreneurial labor in the production of wholesale goods, and profits resulting from the production of capital goods,  $N_{t+1} = \iota V_t + (1 - \alpha - \Omega) Y_t X_t + \Pi_{E,t}$ . Entrepreneurial equity, in turn, is given by

$$V_t = R_t^k Q_{t-1} K_t - R_t (Q_{t-1} K_t - N_t) - \mu \int_0^{\bar{\omega}_t} \omega R_t^k Q_{t-1} K_t f(\omega) d\omega,$$

i.e. the realized return on capital less repayment of loans. Note that the third term on the right-hand side represents the real resources devoted to monitoring entrepreneurs in default; these expenses are borne by entrepreneurs through financing conditions.

Combining the expressions for net worth and equity and log-linearizing gives the following law of motion for net worth:

$$\begin{aligned} (N/K) n_{t+1} &= \iota (\alpha Y X / K + 1 - \delta - R) (q_{t-1} + k_t) + \iota (\alpha Y X / K + 1 - \delta) r_t^k \\ &\quad + \iota R (N/K - 1) r_t + \iota R (N/K) n_t + (1 - \alpha - \Omega) (Y X / K) y_t \\ &\quad + (1 - \alpha - \Omega) (Y X / K) x_t + \delta q_t - \iota D \phi_t \end{aligned} \quad (14)$$

$$\text{with } \phi_t = \log \left[ \mu \int_0^{\bar{\omega}_t} \omega R_t^k Q_{t-1} K_t (\omega) f(\omega) d\omega / DK \right] \text{ and } D = \mu \int_0^{\bar{\omega}} \omega R^k f(\omega) d\omega.$$

## 2.4 Households

A generic household  $z \in [0, 1]$  provides differentiated labor services,  $H_t(z)$ , to the entrepreneurial sector. It also decides, in period  $t - 1$ , over consumption  $C_t(z)$  and, in principle, the wage rate  $W_t(z)$  for the next period. This corresponds to the assumption of a one-period lag in the household's decision-making or, alternatively, a conditioning on last period's information set. In addition, the household is exogenously constrained in reoptimizing its wage rate in the same way as retailers are in reoptimizing prices. However, we assume that households can insure themselves against idiosyncratic income risk resulting from the limited ability to set wages optimally in each period, see Woodford (2003). Households are, therefore, homogeneous with respect to consumption and deposits held with a financial intermediary, and the household's optimization problem can be conveniently analyzed in two stages.

Regarding consumption we adopt the internal habit specification suggested by Amato and Laubach (2004), where the degree of habit formation is indicated by  $\gamma \in [0, 1]$ .<sup>5</sup> Specifically, at

<sup>5</sup>One advantage of this ratio specification with respect to alternative (difference) specifications is that it remains well defined even if current consumption fails to exceed the habit level.

the first stage household  $z$  chooses consumption to maximize

$$E_{t-1} \left\{ \sum_{k=0}^{\infty} \beta^k \left[ \frac{1}{1-\sigma} \left( \frac{C_{t+k}}{C_{t+k-1}^\gamma} \right)^{1-\sigma} - \frac{1}{1+\nu} (H_{t+k}(z))^{1+\nu} \right] \right\}$$

subject to the flow budget constraint

$$\frac{W_t(z)}{P_t} H_t(z) + R_t B_t + \Pi_{H,t} \geq C_t + T_t + B_{t+1},$$

where  $B_t$  denotes real deposits held from  $t-1$  to  $t$ ,  $T_t$  denotes lump-sum taxes and  $\Pi_{H,t}$  represents lump-sum transfers. The latter comprise profits earned by retailers and the equity of entrepreneurs who exit business. Household optimization requires that the flow budget constraint holds with equality and that the household's wealth accumulation satisfies the transversality condition. Let  $\Lambda_t$  denote the household's marginal utility of income at date  $t$ . An approximation of the relevant first-order conditions is then given by

$$-\sigma E_{t-1} \{c_t - \gamma(1-\sigma)c_{t-1} - \beta\gamma[(1-\sigma)c_{t+1} - (1+\gamma(1-\sigma))c_t]\} = (1-\beta\gamma)E_{t-1}\lambda_t, \quad (15)$$

$$E_t(\lambda_{t+1} + r_{t+1}) = \lambda_t. \quad (16)$$

Equation (15) relates the marginal utility of income to lagged, current and future values of consumption, reflecting the time inseparability of utility introduced by habit formation. This condition is supplemented by the standard intertemporal optimality condition in (16).

At the second stage, households decide on wages. The monopolistic power of households follows from the assumption that households' specific labor services are bundled into aggregate labor services according to

$$H_t = \left[ \int_0^1 H_t(z)^{\frac{\xi-1}{\xi}} dz \right]^{\frac{\xi}{\xi-1}}. \quad (17)$$

Given entrepreneurs' demand for aggregated labor services,  $H_t$ , and an optimal allocation of wage expenditure, household  $z$  faces a downward sloping demand function

$$H_t(z) = \left( \frac{W_t(z)}{W_t} \right)^{-\xi} H_t, \quad (18)$$

where  $\xi$  measures the wage elasticity of demand among differentiated labor services.  $W_t$  denotes the wage index

$$W_t = \left[ \int_0^1 W_t(z)^{1-\xi} dz \right]^{\frac{1}{1-\xi}}. \quad (19)$$

Analogously to the case of retailers, a generic household can reoptimize its wage with probability  $1 - \theta_w$  only. Likewise, we assume that wages which are not reoptimized in a given period are indexed to past inflation. The degree of indexation is governed by  $\kappa_w$ . Consequently, if the wage rate for labor services  $z$  has not been reoptimized for  $k$  periods, it amounts to

$W_{t+k}(z) = W_t(z) (P_{t+k-1}/P_{t-1})^{\kappa_w}$ . If instead reoptimization is possible, the household will set  $W_t^*$  set in order to maximize

$$E_{t-1} \left\{ \sum_{k=0}^{\infty} (\beta\theta_w)^k \left[ \Lambda_{t+k} H_{t,t+k}(z) \frac{W_t^*}{P_{t+k}} \left( \frac{P_{t+k-1}}{P_{t-1}} \right)^{\kappa_w} - \frac{1}{1+\nu} (H_{t,t+k}(z))^{1+\nu} \right] \right\}$$

subject to the demand function (18). Note that  $H_{t,t+k}(z)$  stands for the labor supply of household  $z$  in period  $t+k$ , if the most recently optimized wage came into effect in  $t$ . Further, the preference parameter  $\nu$  determines the degree of disutility resulting from the provision of labor services. In the case of a Walrasian labor market, it would correspond to the inverse of the intertemporal elasticity of labor supply. The solution to the above problem satisfies the first-order condition

$$E_{t-1} \left\{ \sum_{k=0}^{\infty} (\beta\theta_w)^k H_{t,t+k}(z) \left[ \Lambda_{t+k} \frac{W_t^*}{P_{t+k}} \left( \frac{P_{t+k-1}}{P_{t-1}} \right)^{\kappa_w} - \frac{\xi}{\xi-1} (H_{t,t+k}(z))^\nu \right] \right\} = 0.$$

A log-linear approximation of this first-order condition, together with (19), implies a dynamic relationship for wage inflation,  $\pi_t^w = \log(W_t/W_{t-1})$ , which is isomorphic to the New Keynesian Phillips Curve derived above:

$$E_{t-1} (\pi_t^w - \kappa_w \pi_{t-1}) = \beta E_{t-1} (\pi_{t+1}^w - \kappa_w \pi_t) + \lambda_w E_{t-1} (\nu h_t - \lambda_t - w_t^r), \quad (20)$$

where  $\lambda_w = (1 - \beta\theta_w)(1 - \theta_w)/(\theta_w(1 + \xi\nu))$ . The real wage,  $w_t^r$ , is linked to inflation and wage inflation in the following way:

$$w_t^r = w_{t-1}^r + \pi_t^w - \pi_t. \quad (21)$$

## 2.5 Monetary Policy

We assume that monetary policy is characterized by an interest rate feedback rule taking the following flexible form:

$$\begin{aligned} r_{t+1}^{nom} &= \rho_1 r_t^{nom} + \rho_2 r_{t-1}^{nom} + \rho_3 r_{t-2}^{nom} + \rho_4 r_{t-3}^{nom} + \\ &\quad \phi_{\pi,1} \pi_t + \phi_{\pi,2} \pi_{t-1} + \phi_{\pi,3} \pi_{t-2} + \phi_{\pi,4} \pi_{t-3} \\ &\quad \phi_{y,1} y_t + \phi_{y,2} y_{t-1} + \phi_{y,3} y_{t-2} + \phi_{y,4} y_{t-3} + \varepsilon_t, \end{aligned} \quad (22)$$

where all the coefficients are taken directly from the (constrained) VAR as in Rotemberg and Woodford (1997) and Amato and Laubach (2003). The relationship between the nominal and real interest rates is, of course, defined as

$$r_{t+1}^{nom} = r_{t+1} + E_t \{ \pi_{t+1} \}. \quad (23)$$

## 2.6 Market Clearing and Equilibrium

The market for final goods clears in every period,

$$Y_t = C_t + I_t + G_t + \mu \int_0^{\bar{\omega}_t} \omega R_t^k Q_{t-1} K_t f(\omega) d\omega, \quad (24)$$

where  $G_t$  denotes public spending.<sup>6</sup> An approximation to (24) gives

$$y_t = (C/Y) c_t + \delta (K/Y) i_t + (DK/Y) \phi_t. \quad (25)$$

Likewise, financial markets clear so that deposits,  $B_{t+1}$ , meet the demand for investment finance,  $Q_t K_{t+1} - N_{t+1}$ .

For the purposes of our exercise, we study the equilibrium dynamics around a non-stochastic steady state. Specifically, given a shock  $\varepsilon_t$  to the interest feedback rule, we consider sequences for the following generic variables:

$$\{\pi_t, \pi_t^w, r_t^k, r_t^{nom}, r_t, w_t^r, x_t, q_t, y_t, c_t, i_t, n_t, h_t, k_t, \lambda_t\}_{t=0}^{\infty}.$$

These variables are matched by the following equilibrium conditions: the New Keynesian Phillips Curve (6), the production function (7), the demand for labor (8), the law of motion for capital (9), investment demand (10), return to capital (12), premium on external funds (13), the evolution of net worth given by (14), the Euler equations (15) and (16), the dynamics of wage inflation (20), and the goods market clearing condition (25). In addition, we use the interest rate feedback rule (22) and the definitions of the real wage (21) and the nominal interest rate (23) to pin down the equilibrium.<sup>7</sup> The implied system of expectational difference equations is solved numerically using the Generalized Schur Decomposition as discussed by Klein (2000). The solution of the model can be represented by a first-order autoregressive structure, which, in turn, is used to compute the impulse responses to a monetary policy shock.

## 3 Empirical Characterization of Transmission

Having introduced our theoretical model, we now turn to the empirical characterization of monetary transmission, i.e. the dynamics of output components, real wage, inflation and the interest rate *as apparent from the data*. Specifically, we use a VAR framework to obtain estimates of the empirical impulse response functions associated with a monetary policy shock. In order

<sup>6</sup>Government spending is included in the model in order to calibrate steady-state ratios. We assume that it is constant, i.e.  $G_t = G$ , and financed exclusively through lump-sum taxes.

<sup>7</sup>Note that the term  $\phi_t$  in equations (14) and (25) is of second-order importance and has no perceptible impact on the dynamic behavior of the economy. The reason already pointed out by BGG is that, in the log-linearized equations, this term is weighted by the steady-state level of monitoring costs relative to the steady-state values of equity and output, respectively. Even for the highest values of  $\chi$  that we consider, the weight of this term does not exceed 0.13 percent in the equity equation and 0.5 percent in the output equation. Therefore we ignore the term in the numerical simulations below.

to ensure that the VAR actually captures the empirical equivalent of the dynamics implied by our theory, the identifying restrictions we use in our VAR have to be consistent with the model. This requires that the timing of dynamic responses in the VAR be no more restrictive than in the model. Consequently, monetary policy shocks are identified by assuming that inflation, real wage, output and its components do not respond contemporaneously to a shock in monetary policy. This is a standard assumption in the empirical literature and can easily be justified from planning and implementation lags such as those incorporated into our model. Likewise, we follow standard practice and allow for four lags in the VAR. The structure of the interest rate feedback rule (22) is imposed in the estimation, since we directly import this rule from the VAR into the model.

Another important note concerns the remaining variables we include in our VAR. The guiding principle here again is correspondence with the theoretical model, taking into account the canon of previous empirical work. Apart from the variables usually considered as the minimum specification, i.e. output ( $y$ ), inflation ( $\pi$ ) and the federal funds rate ( $r^{nom}$ ), we also include the real wage ( $w^r$ ) as well as the components of output, consumption ( $c$ ) and investment ( $i$ ), whose responses we are particularly interested in. Since, in the theoretical model, the dynamics of these variables are driven by the state variables, notably capital and net worth, it seems appropriate to proxy for these variables in the empirical model, as well. We therefore include the inverse of the interest coverage ratio as a proxy variable that captures changes in the financial situation of corporate borrowers. The variable, which we also dub "corporate interest burden" ( $cib$ ) is defined as the ratio of net corporate interest expenditure to pre-tax profits plus interest expenditure. It has been suggested by previous authors in the literature on financial frictions, e.g. Bernanke and Gertler (1995), as a good real-time measure of financial strain in the corporate sector, thus proxying directly for the net-worth channel we would like to examine. Realistically, we allow this variable to respond contemporaneously to changes in nominal interest rates.<sup>8</sup>

Our VAR thus comprises the seven variables (the first two pertaining to period  $t$ , the rest to  $t + 1$ ) contained in

$$Z_t = (r_{t+1}^{nom}, cib_t, w_{t+1}^r, \pi_{t+1}, y_{t+1}, i_{t+1}, c_{t+1})'$$

and takes the following form:

$$T\bar{Z}_t = m + A\bar{Z}_{t-1} + \bar{e}_t, \quad (26)$$

where  $\bar{Z}_t = (Z_t', Z_{t-1}', Z_{t-2}', Z_{t-3}')'$ ,  $T$  is a  $28 \times 28$  identity matrix with a lower triangular  $7 \times 7$

<sup>8</sup>Finding satisfactory proxies for the capital stock is more difficult, which explains the common practice of specifying empirical VARs without capital. The potential pitfalls of this practice have recently been highlighted by Chari, Kehoe and McGrattan (2005). In contrast, Altig et al. (2005) document that for reasonably large VAR specifications, the omission of capital is not very problematic. For the purposes of our own study, we also conducted a small-scale Monte Carlo experiment. Our results (available upon request) strongly confirm the conclusion drawn by Altig et al.

matrix in the upper left corner that contains the coefficients capturing the contemporaneous relationships between the variables in  $Z_t$ .  $m$  is a vector of 28 constants. The  $28 \times 28$  matrix  $A$  contains coefficients in the first seven rows only, since the other rows impose identities. As a consequence, only the first seven elements of the vector  $\bar{\varepsilon}_t$  are different from zero, representing structural shocks. Moreover, since the first row of  $A$  contains the coefficients of the interest rate reaction function, which is also used in the theoretical model, we restrict the coefficients on all variables except inflation, GDP and lagged interest rates to be zero. Hence, under this identification scheme, the first element of the vector  $\bar{\varepsilon}_t$  may be interpreted as a monetary policy shock,  $\varepsilon_t$ . The structure of (26) is very similar to the one considered by Rotemberg and Woodford (1997) and Amato and Laubach (2003), but allows for even more general dynamics following a monetary policy shock. We estimate this VAR recursively by OLS.

The data we use are quarterly US data taken from the NIPA of the BEA (real GDP, real consumption, real investment, real hourly compensation in nonfarm business sector, GDP deflator, corporate profits and net interest payments) and the Board of Governors of the Federal Reserve System (federal funds rate). The data are transformed in the following way: In accordance with the model,  $y$ ,  $i$ ,  $c$  and  $w^r$  are defined as log deviations from constant steady-state growth. Our measure of financial tightness,  $cib$ , is a detrended ratio variable, while inflation  $\pi$  is computed from log differences of the GDP deflator. Finally, the federal funds rate,  $r^{nom}$ , is divided by 400 to obtain a measure for the quarterly interest rate.<sup>9</sup>

The sample we consider is 1980:1 through 2003:4, covering essentially the entire Volcker-Greenspan period to date. Because we wish to identify the historical monetary rule from the VAR, it is important to estimate it over a sample period in which the coefficients of (22) can reasonably be assumed to be constant. According to several authors, including Boivin and Giannoni (2003), policy since the Volcker disinflation of the early 1980s has indeed displayed a high degree of stability.

Turning to the results of our VAR estimation, we begin with the characterization of monetary policy based on estimates from the first equation. As is well-known, the long-run response of the central bank to changes in inflation is an important determinant for the stability of the economy. Our estimates indicate that the FED's policy has satisfied the so-called Taylor Principle in the Volcker-Greenspan period. Specifically, the coefficients on inflation add up to 0.4766, while those on the lagged interest rate sum to 0.7853, implying a long-run response of 2.22, greater than one. This finding corresponds closely with the results reported in Clarida, Galí and Gertler (2000).

Next, we use the estimated VAR to obtain an empirical characterization of the transmission of a monetary policy shock  $\varepsilon_t$ . The impulse responses of all seven variables are depicted in

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<sup>9</sup>Note that output and the other level series do not need to be divided by four, since they only show up as log deviations from steady state, i.e. in percentage terms. In contrast, shocks to the interest rate are in terms of percentage points. Inflation is already measured and expressed at quarterly frequency.

figure 1. Note that impulses are measured in terms of percentage deviations (percentage point deviations in the case of inflation, corporate interest burden and the interest rate) from the unshocked path, following a unit shock in the quarterly federal funds rate. The shaded areas give 90 percent confidence bands, computed by bootstrapping based on 10,000 replications.<sup>10</sup>

The responses of our key variables, output, consumption and investment, show the familiar pattern, i.e. a roughly hump-shaped decline with peak responses after two to five quarters. All of these responses are significant, although the reaction of investment is much larger in percentage terms than the consumption response. Furthermore, we observe a slight but protracted decrease in inflation as well as a significant fall in the real wage. The interest rate declines for roughly one year before it reaches its steady-state level again. Lastly, our "corporate interest burden" variable shows a marked increase following the contractionary monetary shock. This squares well with the intuition that higher interest rates will lead to tighter financial conditions in the corporate sector, even though the relative importance of financial frictions for this result cannot be immediately inferred. Overall, our findings are in line with the stylized facts reported by, for example, Christiano, Eichenbaum and Evans (1999). In the following they will be confronted with the predictions of our theoretical model.

## 4 Estimation Strategy

Having characterized our data and model, we are now in a position to match empirical (VAR) and theoretical (DSGE) impulse responses, thereby obtaining estimates for the structural parameters of our model. Rotemberg and Woodford (1997) were the first to suggest this estimation technique in the context of DSGE models.<sup>11</sup> Similar approaches have subsequently been applied by Amato and Laubach (2003), Boivin and Giannoni (2003), Giannoni and Woodford (2003) and CEE.

Generally, one important question in minimum distance estimation concerns the issue of which moments or auxiliary statistics to match. From an econometric point of view, the moments used in estimation should be as informative as possible, in the sense of bearing strong and distinct relationships with each of the structural parameters. While it is often difficult to evaluate this property in a stringent way, Adda and Cooper (2003) note that the selection of moments may also be guided by other criteria. Economic interest, indeed, would suggest considering aspects of the data that are important in their own right, e.g. because they shed light on the merits of an important theory or because they matter most for economic policy. Against this background, we consider, as the relevant feature to match, the VAR impulse responses characterizing monetary transmission in the data. Importantly, in doing so we concentrate on

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<sup>10</sup>The bootstrap is also used to compute the covariance matrix of the impulse responses that we require for the main estimation exercise, as discussed in the next section.

<sup>11</sup>Note the early use of a similar statistic, merely for specification testing, in Cogley and Nason (1994).

the propagation of one particular shock only, i.e. a shock to monetary policy, remaining agnostic about the complete specification of the data generating process. In our view, this limited-information strategy fits the stylized character of modern macroeconomic models, although it is certainly less ambitious (or trustful of the descriptive value of these models) than full-fledged maximum likelihood estimation.

Formally, define  $\Psi_T^e$  to be the *empirical* impulse response function characterizing our data set of length  $T$ . Note that  $\Psi_T^e$  is not a raw moment but a transformation of the estimates obtained from a VAR which is supposed to capture the empirical counterpart of the dynamics described by our log-linearized model. The model itself, in turn, assigns to each admissible vector of structural parameters  $\theta$  a theoretical impulse response function  $\Psi^t = \Psi(\theta)$ . The binding function  $\Psi(\cdot)$  must be assumed to be injective to ensure identification. Thus we obtain an estimate for the parameter vector of interest,  $\hat{\theta}$ , by minimizing the weighted distance between empirical and theoretical impulse response functions, i.e.  $\Psi_T^e$  and  $\Psi^t$ :

$$\hat{\theta} = \arg \min_{\theta \in \Theta} (\Psi_T^e - \Psi(\theta))' W_T (\Psi_T^e - \Psi(\theta)), \quad (27)$$

where  $W_T$  represents a positive definite weighting matrix, with  $W = \text{plim} W_T$  also being positive definite. Our choice of  $W_T$  is discussed below.

As there is no analytical expression for the relationship between structural parameters and the implied impulse response functions, we rely on numerical methods to obtain a solution for (27). Note, in this context, that our estimation exercise does not share the problem of many other simulation-based estimation techniques, in which repeated simulations have to be made to determine  $\Psi^t$  for a given  $\theta$ . The reason already discussed above is that we focus on the economy's deterministic response to one well-defined shock, abstracting from all other sources of stochastic variation present in the data. Likewise, our estimation problem is somewhat different from typical applications of the so-called Method of Simulated Moments (MSM), where the equivalent of a theoretically derived moment condition can be computed for each of  $T$  (or  $i$ ) observations in the sample. Instead, we basically have no more than one observation of the auxiliary statistic of interest,  $\Psi_T^e$ . Therefore we establish the statistical properties of  $\Psi_T^e$  by means of bootstrapping, prior to the actual minimum distance estimation.

Define  $\Sigma$  as the asymptotic covariance<sup>12</sup> of  $\sqrt{T}(\Psi_T^e - \Psi)$ , and let  $\widehat{Avar}(\Psi_T^e)$  denote our bootstrap estimate for the asymptotic variance of  $\Psi_T^e$ , so that  $\widehat{Avar}(\Psi_T^e) = \widehat{\Sigma}/T$ . Then, in order to obtain efficient estimates,<sup>13</sup> we can choose  $W_T$  to be the optimal weighting matrix  $W^{opt}$ , i.e. the inverse of our estimate of  $\Sigma$ :

$$W^{opt} = \left(\widehat{\Sigma}\right)^{-1} = \left[T\widehat{Avar}(\Psi_T^e)\right]^{-1}. \quad (28)$$

<sup>12</sup>We follow previous authors in this literature and implicitly rule out cases where the asymptotic covariance would be degenerate. For a discussion, see Benkwitz, Lütkepohl and Neumann (2000).

<sup>13</sup>Of course, efficiency here refers to a given choice of an auxiliary statistic to match.

Although several other authors have acknowledged the possibility and promise of using this weighting matrix, we are not aware of any application. Boivin and Giannoni (2003), for instance, point at difficulties with their minimization algorithm. Clearly, estimating large covariance matrices may pose problems in practice, but throughout our exercises we have not encountered any obstacles that would preclude their use. One alternative weighting matrix that was chosen by several other authors is a diagonal matrix,  $W^{diag}$ , whose inverse has the same diagonal entries as the inverse of  $W^{opt}$ , while all off-diagonals are set to zero. In other words,  $W^{diag}$  is a matrix that has, on its diagonal, the reciprocal values of the asymptotic variance of the impulse responses. Using this weighting matrix amounts to embracing an optical criterion in that the theoretical impulse responses are made to be as close to the empirical ones as possible, in terms of point-wise standard deviations. Despite its appeal, this is perhaps not the most convincing criterion, insofar as it completely ignores the probabilistic relationship between different impulse responses. In particular, as Dedola and Neri (2004) remark, a diagonal weighting matrix treats deviations from the point estimates as independent, while in fact they show substantial correlation. This observation is related to a similar point raised by Sims and Zha (1999), who note that the standard one-deviation error bands considered point-wise do "not directly give much information about the forms of deviation from the point estimate of the response function that are most likely." Below, we will report estimates for both choices of  $W_T$ .

One further choice concerns the length of the series to be considered. We match impulse responses for output, consumption, investment, real wage, inflation and the interest rate over the first twelve quarters following the impact. These are all six series for which there is a clear correspondence between the model and the VAR. Moreover, three years appear to be a reasonable period in order to gauge the effects of a one-time nominal shock. Indeed, most economists would agree (and our VAR results suggest) that real variables should largely return to their steady-state values within that time.<sup>14</sup>

Invoking the arguments in McFadden and Newey (1994), we will rely on the following expression for the asymptotic variance of our estimator,

$$\sqrt{T}(\hat{\theta} - \theta) \rightarrow^d N\left(0, (G'WG)^{-1}(G'W\Sigma WG)(G'WG)^{-1}\right), \quad (29)$$

which, in the case of using the optimal weighting matrix, simplifies to

$$\sqrt{T}(\hat{\theta} - \theta) \rightarrow^d N\left(0, (G'\Sigma^{-1}G)^{-1}\right), \quad (30)$$

where  $G = \nabla_{\theta}\Psi^t$  denotes the Jacobian of the impulse response function generated from the model. All matrices contained in (29) and (30) can be estimated consistently. Specifically,

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<sup>14</sup>Still, to check for the robustness of our findings, we also report estimates based on matching, respectively, eight and sixteen periods after the impact. See table 2 below.

estimates of  $W$  and  $\Sigma$  are obtained as by-products of our bootstrapping procedure, and  $G$  can be obtained from numerical differentiation. Thus, the asymptotic variance of  $\hat{\theta}$  reads as

$$\widehat{Avar}(\hat{\theta}) = \left(\widehat{G}'W_T\widehat{G}\right)^{-1} \left(\widehat{G}'W_T\widehat{Avar}(\Psi_T^e)W_T\widehat{G}\right) \left(\widehat{G}'W_T\widehat{G}\right)^{-1}, \quad (31)$$

or, for  $W = W^{opt}$ :

$$\widehat{Avar}(\hat{\theta}) = \left(\widehat{G}'\left(\widehat{Avar}(\Psi_T^e)\right)^{-1}\widehat{G}\right)^{-1}, \quad (32)$$

allowing us to report asymptotic standard errors for our estimates.

## 5 Results

### 5.1 Parametric Setup

We partition the parameters of our structural model in three groups. The first group comprises parameters that can be fixed before the actual estimation exercise, because their values are inferable from first moments of the data or otherwise uncontroversial. Specifically, we set the time discount rate,  $\beta$ , to 0.99, while the quarterly capital depreciation rate,  $\delta$ , is fixed at the usual 2.5 %. The output shares of household labor,  $\Omega$ , and capital,  $\alpha$ , take the standard values of 64 % and 35 %, respectively. The remaining 1 % accrue to entrepreneurs' labor in our model. The elasticity of substitution among alternative differentiated goods,  $\epsilon$ , is set to eight. This is close to the value reported by Rotemberg and Woodford (1997) and implies a plausible steady-state markup of approximately 15 percent. Lastly, in terms of output components, we fix the share of government spending at 20 %, the long-run average in the data. Note that the remaining steady-state values, i.e. of capital, output, net worth and consumption are updated for each parameter configuration, to be consistent with the micro structure of the model economy. In fact, these levels are functions of the primitives of the contracting problem that is at the root of the financial accelerator. However, these primitives are not separately identified - only the "reduced form" elasticity of financing costs with respect to net worth is, and it is one of the parameters we are estimating ( $\chi$ ). Thus we explicitly make steady-state values a function of  $\chi$ , where the exact functional relationship is based on an assumed variation of two of the deep parameters, leaving the third one fixed.<sup>15</sup>

The second group of parameters are those characterizing monetary policy. As detailed before, we specify a fairly general interest rate feedback rule, whose coefficients are estimated as a by-product of our VAR. These estimates are directly fed into our structural model, so as to ensure consistent definitions of the monetary policy rules in the model and the VAR.<sup>16</sup>

<sup>15</sup>See appendix A.3 for a detailed exposition.

<sup>16</sup>Note that we refrain from treating the Taylor rule coefficients as "generated regressors". Basically, they are regarded here as given, as would be done in standard calibration or simulation exercises.

Finally, we are left with the group of parameters we would like to estimate. The vector comprises nine coefficients, i.e.  $(\lambda_p, \kappa_p, \lambda_w, \kappa_w, \chi, \varphi, \sigma, \gamma, \nu)$ . However, we decide to drop the inverse of the intertemporal elasticity of labor supply,  $\nu$ , from that list to reduce the dimensionality of our estimation exercise and reflecting concerns that this parameter is poorly identified.<sup>17</sup> In our baseline setup, we consider  $\nu = 3$ . This value conforms with the predominant evidence, from microeconomic studies, of relatively low labor supply elasticities, see the discussion in Pistaferri (2003). Note further that we cannot identify the Calvo parameter  $\theta_w$  individually, given that it only appears jointly with the demand elasticity  $\xi$ . Thus, we simply report the slope parameter  $\lambda_w$  from the wage inflation equation (20). From this value, consistent combinations of  $\theta_w$  and  $\xi$  can be computed. For comparability, we proceed symmetrically with respect to the slope parameter  $\lambda_p$  from the Phillips curve equation (6); without strategic complementarities in retailers' production, the Calvo parameter  $\theta_p$  can actually be inferred from  $\lambda_p$ . Recall next, that  $\kappa_p$  and  $\kappa_w$  are the indexation parameters from equations (6) and (20);  $\chi$  is the elasticity of financing costs with respect to borrowers' net worth (equation (13));  $\varphi$  denotes the elasticity of the price of capital with respect to the investment-capital ratio (equation (10));  $\sigma$  is the preference parameter from our power utility function; and, lastly,  $\gamma$  represents the habit formation term from equation (15). In accordance with theory,  $\kappa_p$ ,  $\kappa_w$  and  $\gamma$  are constrained to be between 0 and 1;  $\lambda_p$ ,  $\lambda_w$  must be positive,  $\sigma$  greater than one and  $\chi$  and  $\varphi$  non-negative.

## 5.2 Point Estimates

Table 1 provides the results of our baseline estimation exercise. We estimate on the basis of (27), once using efficient weighting,  $W^{opt}$ , and once the simpler diagonal weighting matrix,  $W^{diag}$ , that has been used exclusively in the previous literature. Standard errors are in parentheses, except for parameters that were estimated to be on a bound. Although confidence intervals are relatively wide for certain parameters, our estimates generally have sufficient precision to judge the relative importance of different model features. Indeed, some parameters are pinned down quite precisely, especially using the efficient weighting matrix. Furthermore, all estimates lie in a reasonable range.

Consider first the results for the 'efficient weights' estimation in column 3. Nominal rigidities in price setting appear to be very pronounced, as can be inferred from the low coefficient we find for  $\lambda_p$ . Even taking standard errors into account, this estimate indicates significant sluggishness in prices. The point estimate for  $\lambda_w$  is considerably larger and less precisely estimated, suggesting weaker, if still important, rigidities in wage setting. Remember that low estimates for  $\lambda_p$  and

<sup>17</sup>Apart from our own evidence on this point, this is also the finding of several independent studies using different estimation methods, e.g. Dedola and Neri (2004). Table 2 below reports robustness checks for the case where we set  $\nu$  to 1 (unit elasticity) and 5, respectively. The most noticeable effect of variation in  $\nu$  is on estimates of  $\lambda_w$ , as suggested by equation (20).

$\lambda_w$  are consistent with high values of the Calvo parameters  $\theta_p$  and  $\theta_w$  and/or a high value of the demand elasticity  $\xi$ , in effect implying markedly flat Phillips and wage inflation curves.<sup>18</sup> Our results thus align with the findings reported by Giannoni and Woodford (2003) and suggest a strong role for nominal rigidities, especially in prices. In addition, the optimal parameter vector implies full indexation of both labor and goods contracts, since both  $\kappa_p$  and  $\kappa_w$  are estimated to be equal to the upper bound of one. This again confirms earlier findings by Giannoni and Woodford (2003) as well as Boivin and Giannoni (2003). Next, the coefficient associated with capital adjustment costs,  $\varphi$ , is estimated to be highly significant at 0.6464. The point estimate implies that a one percent increase in the investment-capital ratio raises the price of capital by roughly 0.65 percent, a high but plausible number. Likewise, our estimate of  $\sigma$  falls into the usual range: in the absence of habit formation, a power utility coefficient of 3.64 would imply an intertemporal elasticity of substitution of 0.27. Interestingly, habit formation actually appears to be very mild, with  $\gamma$  estimated insignificantly at 0.1206. This is in contrast with results found by Giannoni and coauthors and casts doubt on the claim that habit formation is essential to obtain a sufficient match between theory and data. Finally, our main parameter of interest,  $\chi$ , is estimated at sizeable 0.0672, implying that a one percent decrease in the net worth to capital ratio raises the cost of external finance by almost 7 basis points per quarter. While this value is a little higher than the number assumed in BGG's simulations, our estimate is not statistically significant, with a t-statistic of 1.48. Accordingly, it is not quite clear yet what is the quantitative importance of financial frictions for obtaining a good match between our theoretical model and the data.

Column 4 of table 1 reproduces the corresponding results for the estimation using the simple diagonal weighting matrix. As mentioned above, the main difference from the case of efficient weighting is that now estimates are chosen so as to minimize the simple sum of point-wise distances between empirical and theoretical impulse responses, in terms of standard deviations. While greater weight is, thus, given to more precisely estimated impulse responses, the estimation does not take into account any correlation between different points of the impulse response functions. Overall, the estimates are relatively close to the ones discussed above, although standard errors are considerably larger.<sup>19</sup> Nominal rigidities in prices are again estimated to be strong, with  $\lambda_p$  taking a very low value. The new estimate for  $\lambda_w$  is also in the same ballpark

<sup>18</sup>To the extent that very strong nominal rigidities seem to be at odds with microeconomic evidence on price setting, our results highlight the importance of finding additional model features that reduce the pass-through of prices into marginal costs. Along these lines, for instance, Eichenbaum and Fisher (2004) consider firm-specific capital in the retail sector combined with a non-constant elasticity of substitution among differentiated goods. Thus even low macroeconomic estimates of  $\lambda_p$  can be reconciled with plausible values of  $\theta_p$ .

<sup>19</sup>Note that a few authors appear to have reported standard errors based on the same asymptotic formulae we use but additionally dividing (31) by  $\sqrt{T}$ , where T denotes the number of observations used in estimating the VAR. While this would be adequate in the case of a standard GMM problem with T distinct observations, it is incorrect here, as was outlined in the previous section. Clearly, however, division by  $\sqrt{T}$  makes standard errors seem much smaller, roughly by a factor of 10.

as the value in column 3. Next, estimates for  $\kappa_p$  and  $\kappa_w$  confirm our previous findings on the indexation of contracts, even though  $\kappa_p$  is now estimated just below its upper bound of one but significantly different from zero. The estimate for  $\varphi$  is somewhat lower than before, whereas  $\sigma$  and  $\gamma$  are estimated to be slightly higher. Lastly, our central parameter of interest,  $\chi$ , is estimated at 0.0616, very close to the previous estimate but far from significant.

Taken together, the results suggest that sensible parameter estimates can be obtained from our estimation exercise. Specifically, explaining the impulse responses to a monetary policy shock appears to require strong nominal rigidities, especially in prices. In addition, we find evidence for (nearly) full indexation of contracts and sizeable capital adjustment costs. At the same time, our estimation lends only mild support for the presence of financial accelerator effects. Furthermore, habit formation does not seem to have a role to play in bringing our model in line with the data.

In some cases, however, standard errors are relatively large. Moreover, the exact shape of the criterion function is unknown, suggesting that further tests should be conducted to draw firm conclusions about the relevance of all features encompassed by our model. Before tackling this issue, we reproduce, in figure 2, the impulse responses implied by the structural parameter estimates given in table 1. As can be seen from the graph, the empirical impulse responses are tracked quite well by the model evaluated at our parameter estimates. Both the magnitude and the persistence of the impulse responses generated by the VAR are replicated, and the model-based responses remain consistently within the confidence bands. Not surprisingly, the better graphical fit is obtained by the parameter vector from the last column of table 1. This follows immediately from the criterion function and may explain in part why other authors using minimum distance methods have tended to opt for a diagonal weighting scheme. Note, however, that optical fit is not necessarily the most convincing criterion in that it fails to take into account the full probabilistic pattern of impulse responses.

### 5.3 The Impact of Parameter Perturbations

To get some additional insight into the effects of some features of the model, consider two perturbations from our estimated parameter vector as reported in the last column of table 1. First, in figure 3, we set the value of  $\chi$  to zero, corresponding to the case without financial frictions. All other parameters remain at their estimated values for this exercise. In comparison with the baseline picture, the most striking changes are visible from the responses of investment and, somewhat less, output and the real wage. Given that financial frictions tend to reinforce fluctuations in investment, the investment response is now considerably weaker. Without financial frictions, investment falls by nearly half of the decline observed previously in figure 2. At the same time, consumption shows only a mild change in the opposite direction, highlighting the

interest of looking at individual output components. Indeed, if consumption and investment were not taken into account individually, the parameter configuration underlying figure 3 would look very sound, given the good fit with the empirical *output* series. However, empirical investment differs substantially from the theoretical impulse responses. The incremental information provided by the component series can thus be very valuable in judging features of the model which, like the financial accelerator, imply distinct compositional effects.

Another variation from our estimated values is analyzed in figure 4. There, we set the habit parameter  $\gamma$  to its upper-bound value of one. As suggested by the notion of habit formation, consumption now drops much less in response to the initial shock but smooths out the adjustment in a protracted decline. Other series are not affected very much.

Similar perturbation exercises can be made for all other features of the model. Our general impression is that the impulse responses are quite informative about the parameters we seek to estimate, since even small changes tend to have clear effects on the shape of different impulse response series. For instance, variation in the slope parameter  $\lambda_p$  has a considerable impact on all impulse responses, especially inflation and the real wage. Similarly,  $\lambda_w$  and the indexation parameter  $\kappa_p$  have a clear bearing on the shape and magnitude of the inflation and real wage responses, whereas the effects of varying  $\kappa_p$  are more limited. Investment, in turn, is strongly affected by  $\varphi$ : the higher this parameter, the lower and more protracted the fall in investment. Likewise, higher values of  $\sigma$  naturally dampen the consumption response. Clearly these findings are good news for our empirical endeavor to identify the parameters of the model. They also suggest that, if the estimates in table 1 are sometimes not very precise, this is not because the model's parameters do not affect the economy's response to a monetary shock. Rather, the likely reason is that the model is fairly flexible and thus provides at least a decent fit with the data for a range of different parameter configurations. Whether or not at least some features of the model are indispensable for its empirical success will be addressed in the next section. First, it should be pointed out that the results obtained for our baseline estimation are nicely confirmed by a number of robustness checks reported in table 2. We consider the case where estimation, always using efficient weights, is based on matching shorter (eight quarters) and longer (sixteen quarters) series of impulse responses than in our baseline case (twelve quarters). In addition, we report estimates for different values of the preset labor supply parameter  $\nu$ .

## 5.4 Distance Metric Tests

The central question we wish to address in this paper refers to the quantitative importance of various model ingredients. In fact, our model nests a number of interesting special cases, such as strong habit formation or the absence of financial frictions. In order to judge the severity of these and other restrictions, a first informative statistic is provided by the standard errors in

tables 1 and 2. However, given the unknown, possibly irregular shape of the criterion function, we prefer to rely on additional evidence. We therefore propose to use a distance metric test of specific model restrictions as presented in Wooldridge (2002, ch. 14.6). In spirit the test is very close to a likelihood-ratio test. Specifically, we compute the loss functions (using efficient weighting, which is now essential for the validity of the approach) for restricted models in which one parameter is pre-fixed at a given value of interest and all other parameters are estimated. Intuitively, if the loss functions differ greatly between the restricted and the unrestricted model, we can reject the null that the parameter takes on the assumed value. The test statistic in our case looks as follows:

$$(L_r^* - L_u^*) \sim^a \chi^2(\# \text{ restrictions})$$

and is asymptotically distributed as Chi-squared with degrees of freedom equal to the number of restrictions imposed.  $L^*$  denotes the value of the loss function at its optimum, i.e.

$$\begin{aligned} L^* &= \min T(\Psi_T^e - \Psi(\theta))' \widehat{\Sigma}^{-1} (\Psi_T^e - \Psi(\theta)) \\ &= \min (\Psi_T^e - \Psi(\theta))' \left( \widehat{Avar}(\Psi_T^e) \right)^{-1} (\Psi_T^e - \Psi(\theta)), \end{aligned}$$

and indices  $r$  and  $u$  stand for the restricted and unrestricted minimization problem, respectively.

To begin with, we revisit the finding that the habit parameter,  $\gamma$ , was consistently estimated to be close to its lower bound of zero, suggesting a minor role for habit formation. We reestimate our structural parameter vector, now forcing  $\gamma$  to zero. The results of this restricted estimation exercise are provided in table 3, along with several further cases. Although the optimum loss function value is slightly higher than in the unrestricted case, the difference is clearly too small to reject the null hypothesis. Note that this conclusion aligns well with the evidence already provided by the standard errors in tables 1 and 2.

Considering, next, the restriction of  $\gamma = 1$ , we observe a markedly different result. Imposing strong habit formation causes the model a substantial loss of fit with respect to the unrestricted model. Accordingly, we can reject this null hypothesis at any conventional level (p-value 0.0003). The main reason for the descriptive inaptitude of the restricted model appears to be the distinct impact of habit formation on the consumption response that was already visible from figure 4. Even when other parameters are allowed to adjust, the dampening of the initial consumption response goes counter to what the VAR impulse responses show. It would thus seem that our model admits a moderate extent of internal habit formation at most in order to match the empirical evidence.

Apart from preference parameters, other hypotheses of obvious interest concern the real frictions embedded in the most general model. Thus, we next examine the loss in descriptive quality of our model when capital adjustment costs are assumed to be absent. As the results in

column 4 indicate, this restriction is forcefully rejected by the data. Indeed, the minimum loss deteriorates substantially - to more than six times the loss of the best unrestricted model. At the same time, the remaining parameter estimates take quite extreme values. Real frictions in the investment process thus appear to be critical for the descriptive success of the model, notably to generate the protracted decrease in investment. While this result is not very surprising, a less predictable observation can be made regarding the specific type of financial frictions we have embedded into our model. Given the inconclusive evidence regarding the quantitative importance of financial frictions from our previous estimates, we formally test the restriction of no financial accelerator effects. More precisely, in our last experiment we set  $\chi$  to zero and re-estimate all other parameters of the model. The results in column 5 indicate that this restriction cannot be formally rejected. Although financial frictions improve the model's fit with the data, they do not do so strongly enough to produce significant support for  $\chi > 0$ . In terms of point estimates, the main consequence of fixing  $\chi$  at zero is a decrease in the capital adjustment parameter,  $\varphi$ , along with a further decrease in  $\lambda_p$  and a higher estimate of  $\sigma$ . As it turns out, the absence of financial frictions can be comfortably offset by somewhat weaker capital adjustment costs, while the opposite is not true. In this sense, the quantitative importance of financial frictions is relatively limited.

A nice feature throughout is that our distance metric tests fully confirm the results from simpler Wald-type tests based on point estimates and the associated standard errors. In small samples, this equivalence need not necessarily hold, so we have reason to feel all the more reassured about our conclusions as to the relative importance of the different model components we have studied.

## 6 Conclusion

One of the ongoing challenges in the macroeconomic literature, according to Woodford (2003), is to develop a "fully realistic quantitative model of the monetary transmission mechanism". We try to contribute to this research agenda by evaluating the relative importance of different features encompassed by a candidate model. The idea is to find out which aspects of the real and the nominal side of a New Keynesian model are crucial to account for the stylized facts of monetary transmission, as summarized by a typical set of empirical impulse response functions. In particular, we wish to evaluate the importance of financial frictions. To this purpose, we propose a model which embeds Bernanke, Gertler and Gilchrist's (1999) financial accelerator into a medium-scale DSGE framework. In order to obtain estimates for the structural parameters of our model, we use a minimum distance strategy that matches the impulse responses implied by the model with those estimated from US data for the Volcker-Greenspan period. Particular

emphasis is given to explaining not only the response of aggregate output but also the individual behavior of consumption and investment. Moreover, we explicitly take correlation between different impulse responses into account by using an efficient weighting scheme in our minimization. This procedure also lends itself nicely to an insightful evaluation, through distance metric tests, of individual features that are nested in the most general model.

Our model, evaluated at the parameter estimates, is able to reproduce quite well the shape and magnitude of the empirical impulse responses. For this to be the case, the model requires strong nominal rigidities in prices and slightly less so in wages. There is also evidence for a significant degree of price indexation and against strong habit formation in consumption. In addition, our results ascribe an important role to capital adjustment costs - apparently an indispensable feature on the real side of our New Keynesian model. In contrast, the financial accelerator itself seems less important than we would have conjectured. Although we obtain sizeable point estimates for the relevant parameter, they fail to be statistically significant. The same conclusion is suggested by our distance metric tests, which show financial frictions to have only a marginal impact on improving the model's fit with the data.

In a sense, this finding may lend support to the widespread use of DSGE models that refrain from incorporating financial accelerator effects. An obvious caveat is that we focus on the propagation of one shock only, singling out monetary transmission as the relevant benchmark of empirical success. It is, therefore, conceivable that financial frictions have a more crucial role to play as the model is confronted with additional aspects of the data. Similarly, one could consider an extended version of the baseline financial accelerator model that allows for heterogeneity across sectors. Gertler and Gilchrist (1994), for instance, report that small firms contract substantially relative to large firms after a monetary tightening, so the assumption of homogeneous responses across firms may be overly restrictive. We think our framework is well suited to address these issues in future research.

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## A The Financial Accelerator

In this appendix, we sketch the microfoundations of the financial accelerator model borrowed from BGG. Its core element is a problem of costly state verification between borrowers and lenders, giving rise to an external finance premium that is inversely related to borrowers' net worth positions. The following draws on a shorter exposition of the problem contained in Gertler, Gilchrist and Natalucci (2003).

### A.1 Debt Contract

To illustrate the contracting problem between borrowers and lenders, we provide an analysis for the steady state, where aggregate risk is absent. Let  $N$  denote the steady-state level of net worth,  $Q$  the price of capital (equal to one in steady state) and  $K$  the steady-state level of the capital stock. The entrepreneur borrows  $QK - N$  to invest  $K$  units of capital in a project. Furthermore, let  $R^k$  denote the aggregate steady-state return on capital. The return on the project of an individual entrepreneur is  $\omega R^k$ , where  $\omega$  represents a multiplicative lognormal shock with mean one, i.e.  $\ln(\omega) \sim N(-\frac{1}{2}\sigma_\omega^2, \sigma_\omega^2)$ . For a given realization of the idiosyncratic shock  $\omega$ , the total payoff on the entrepreneur's capital is thus  $\omega R^k QK$ . Note that  $\omega$  is unknown to both the entrepreneur and the lender prior to the investment decision. Even after the realization of the idiosyncratic shock, the lender can only observe  $\omega$  by paying a proportionate monitoring cost,  $\mu\omega R^k QK$ . Lenders are assumed to be (competitive) financial intermediaries who earn zero profits in equilibrium and are able to perfectly diversify idiosyncratic credit risk. Accordingly, their opportunity cost is  $R$ , the riskless interest rate.

Given this setup, the optimal loan contract can be shown to specify a threshold value  $\bar{\omega}$  for the idiosyncratic shock such that if  $\omega \geq \bar{\omega}$ , the borrower pays the lender the fixed amount  $\bar{\omega} R^k QK$  and keeps the equity  $(\omega - \bar{\omega}) R^k QK$ . Alternatively, if  $\omega < \bar{\omega}$ , the borrower declares bankruptcy, the lender monitors the borrower and receives  $(1 - \mu)\omega R^k QK$  in residual claims net of monitoring costs. In equilibrium, loan contracts must satisfy the condition that the intermediary earn his opportunity costs, i.e.

$$\left( (1 - \mu) \int_0^{\bar{\omega}} \omega f(\omega) d\omega + \bar{\omega} \int_{\bar{\omega}}^{\infty} f(\omega) d\omega \right) R^k QK = R(QK - N). \quad (\text{A1})$$

The optimal contract maximizes the payoff to the entrepreneur subject to (A1). Given constant returns to scale, the threshold value  $\bar{\omega}$  determines the division of expected gross payoff,  $R^k QK$ , between borrower and lender. Let  $\Gamma(\bar{\omega}) = \int_0^{\bar{\omega}} \omega f(\omega) d\omega + \bar{\omega} \int_{\bar{\omega}}^{\infty} f(\omega) d\omega$  denote the gross share of the payoff going to the lender, while  $\mu G(\bar{\omega}) = \mu \int_0^{\bar{\omega}} \omega f(\omega) d\omega$  denotes the expected share pertaining to monitoring costs. The payoff share going to the entrepreneur is thus given by

$1 - \Gamma(\bar{\omega})$ . Defining  $k = QK/N$  and  $s = R^k/R$ , we can set up the Lagrangian for the problem

$$L = (1 - \Gamma(\bar{\omega})) sk + \lambda [(\Gamma(\bar{\omega}) - \mu G(\bar{\omega})) sk - (k - 1)].$$

The following optimality conditions are obtained:

$$\begin{aligned} \frac{\partial L}{\partial \bar{\omega}} &: \Gamma'(\bar{\omega}) - \lambda(\Gamma'(\bar{\omega}) - \mu G'(\bar{\omega})) = 0, \\ \frac{\partial L}{\partial k} &: \Upsilon(\bar{\omega}) s - \lambda = 0, \\ \frac{\partial L}{\partial \lambda} &: (\Gamma(\bar{\omega}) - \mu G(\bar{\omega})) sk - (k - 1) = 0, \end{aligned}$$

where  $\Upsilon(\bar{\omega}) \equiv 1 - \Gamma(\bar{\omega}) + \lambda(\Gamma(\bar{\omega}) - \mu G(\bar{\omega}))$ . Rearranging gives

$$s(\bar{\omega}) = \frac{\lambda}{\Upsilon(\bar{\omega})} \quad (\text{A2})$$

and

$$k(\bar{\omega}) = \frac{\Upsilon(\bar{\omega})}{1 - \Gamma(\bar{\omega})}, \quad (\text{A3})$$

where the Lagrange multiplier,  $\lambda$ , is now also defined as a function of  $\bar{\omega}$ , by virtue of the first optimality condition noted above:  $\lambda(\bar{\omega}) = \Gamma'(\bar{\omega}) / (\Gamma'(\bar{\omega}) - \mu G'(\bar{\omega}))$ . BGG show that both  $s'(\bar{\omega}) > 0$  and  $k'(\bar{\omega}) > 0$ . This ensures the existence of a relationship

$$k = \psi(s), \text{ with } \psi'(s) > 0 \quad (\text{A4})$$

that links the external finance premium,  $s$ , to the ratio between capital and entrepreneurial net worth,  $k$ . This relationship is the key feature of the financial accelerator.

To determine  $\bar{\omega}$ , we proceed as follows. The aggregate return on capital in steady state, implied by (11), is given by

$$R^k = \alpha XY/K + (1 - \delta),$$

while steady-state net worth is given by

$$N = \iota V + (1 - \alpha - \Omega)XY,$$

where  $V = (1 - \Gamma(\bar{\omega})) R^k QK$ . Combining these expressions implies

$$\beta/k(\bar{\omega}) = \iota(1 - \Gamma(\bar{\omega}))s(\bar{\omega}) + \frac{1 - \alpha - \Omega}{\alpha}(s(\bar{\omega}) - \beta(1 - \delta)), \quad (\text{A5})$$

so that  $\bar{\omega}$  can be determined for given values of  $(\Omega, \alpha, \beta, \delta, \mu, \iota, \sigma_{\bar{\omega}}^2)$ .

## A.2 Log-linearization

All derivations in the previous subsection pertain to the non-stochastic steady state of the model. However, BGG establish that, with the addition of aggregate uncertainty, a positive

relationship between the external finance premium and the capital to net worth ratio continues to hold. Specifically, this relationship can be written as

$$\frac{Q_t K_{t+1}}{N_{t+1}} = \psi \left( \frac{E_t R_{t+1}^k}{R_{t+1}} \right). \quad (\text{A6})$$

As in steady-state equation (A4) above, therefore, (A6) provides a link between the entrepreneur's demand for physical capital relative to his current net worth and the wedge between the expected return to capital,  $E_t R_{t+1}^k$ , and the safe rate,  $R_{t+1}$ . Log-linearizing (A6) gives

$$K/N (q_t + k_{t+1} - n_{t+1}) = \psi' (R^k/R) R^k/R (E_t r_{t+1}^k - r_{t+1}) \quad (\text{A7})$$

or

$$E_t r_{t+1}^k - r_{t+1} = -\chi (n_{t+1} - q_t - k_{t+1}), \quad (\text{A8})$$

where  $\chi = \frac{\psi(R^k/R)}{\psi'(R^k/R)} \frac{R}{R^k}$ . Note that while the precise functions  $\psi$  and  $\psi'$  are unknown, the relevant steady-state values can be readily obtained as follows. Define  $g$  as the function that relates  $\bar{\omega}$  to  $s$  given by (A2) and  $h$  as the function that relates  $\bar{\omega}$  to  $k$  given by (A3). The respective derivatives are as follows:

$$\begin{aligned} g' &= \frac{\lambda' \Upsilon - \lambda \Upsilon'}{\Upsilon^2}, \\ h' &= \frac{\Upsilon' (1 - \Gamma) + \Upsilon \Gamma'}{(1 - \Gamma)^2}. \end{aligned}$$

Thus we have  $k = \psi(s) = h(g^{-1}(s))$  and  $\psi'(s) = h'/g'$ , implying that

$$\chi = \frac{\psi(R^k/R)}{\psi'(R^k/R)} \frac{R}{R^k} = \frac{g'}{h'} \frac{k}{s} = \frac{\lambda'/\lambda - \Upsilon'/\Upsilon}{\Upsilon'/\Upsilon + \Gamma'/(1 - \Gamma)},$$

where all functions are evaluated at the threshold value  $\bar{\omega}$  determined by (A5).

### A.3 Numerical Implementation

Apart from the parameters  $\alpha, \beta, \delta$  and  $\Omega$ , which are calibrated from first moments of the data and thus taken as given throughout, the microfoundations of the financial accelerator were shown to depend on three additional parameters:  $\sigma_\omega^2$ , the variance of idiosyncratic shocks to the return on capital;  $\mu$ , the percentage rate of bankruptcy costs; and  $\iota$ , the entrepreneurs' natural rate of survival. The combination of these parameters determines, in a non-trivial way, the relevant steady-state variables of the model and implies a value for  $\chi$ , the "reduced form" parameter capturing financial frictions. As we cannot identify  $\sigma_\omega^2$ ,  $\mu$  and  $\iota$  separately and therefore estimate  $\chi$  instead, we have to make an assumption as to which values of the former should be attributed to a specific value of the latter. This is important to ensure consistency between a given value of  $\chi$  and the steady-state values imposed during estimation. Implicitly, we are thus making the steady state of the model (or, more precisely, those steady-state values not already pinned down

otherwise) a function of  $\chi$ , by attributing to each possible value of  $\chi$  a precise combination of deep parameters. The range of possible choices is substantially narrowed by three simultaneous considerations. First, the "deep" parameters  $\sigma_{\omega}^2$ ,  $\mu$  and  $\iota$  should be realistic in their own right. In practice, we would thus like to set them close to the values proposed by BGG. Second, variations in the deep parameters should allow  $\chi$  to take on any possible value between 0 and, say, 0.1, reflecting every possible situation between no and very strong financial frictions. Finally, in any of these situations, steady-state values themselves should be realistic, i.e. imply sensible magnitudes for default probabilities, monitoring expenditure, the net worth to capital ratio and output shares. As a guideline, we consider again the values put forward by BGG, e.g. a net worth to capital ratio of 0.5, which in turn implies a plausible ratio of corporate debt to GDP of around one. Requiring all three aspects leaves little other possibility than associating changes in  $\chi$  with simultaneous changes in  $\mu$  and  $\iota$ . In particular, variation in only one of the deep parameters would imply unrealistically large deviations from the steady-state values posited by BGG. Thus, we fix  $\sigma_{\omega}^2$  at 0.27, essentially equal to BGG, and associate variations in  $\chi$  between 0 and nearly 0.1 with simultaneous, proportionate variation in  $\mu$  between 0 and 0.4, and  $(1 - \iota)$  between 0.012 and 0.03. The latter interval is symmetric about BGG's choice of 0.021, while the interval for  $\mu$  comprises BGG's choice of 0.12 and covers all cases between no and very substantial monitoring costs. Thus specified, the steady-state risk premium can take values between 0 and 4 % p.a., with a center point of 2 % precisely when financial frictions are close to the level assumed in BGG. Although the other crucial steady-state values do not vary much with  $\chi$ , as desired, we still ensure in our estimation that they are updated at each step in order to be consistent with the microfoundations.

In addition, we ascertained that the paper's main findings are actually not affected by the steady-state adjustment just described. As an important example, the insignificance of the parameter governing financial frictions is perfectly robust to the omission of any steady-state adjustment. Specifically, when we repeat the relevant distance metric test reported in table 3, but now maintaining all steady-state values implied by the unrestricted point estimate for  $\chi$  (from table 1), the test statistic remains minuscule and does not allow to reject the null of no financial frictions.

## B Tables and Figures

**Table 1: Estimates of structural parameters - baseline model**

Parameter	Meaning	Efficient Weighting	Diagonal Weighting
$\lambda_p$	price rigidities (low $\lambda_p$ = strong rigidities)	0.0034 (0.0017)	0.0032 (0.0037)
$\kappa_D$	price indexation	1.0000 ----	0.8965 (0.3171)
$\lambda_w$	wage rigidities (low $\lambda_w$ = strong rigidities)	0.0160 (0.0100)	0.0249 (0.0174)
$\kappa_w$	wage indexation	1.0000 ----	1.0000 ----
$\chi$	financial accelerator	0.0672 (0.0453)	0.0616 (0.1390)
$\varphi$	capital adjustment costs	0.6464 (0.1594)	0.5075 (0.5072)
$\sigma$	power utility parameter	3.6382 (1.1576)	4.0967 (3.6763)
$\gamma$	consumption habits	0.1206 (0.2897)	0.2659 (0.7877)
loss function		30.99	16.31

**Table 2: Robustness checks for baseline specification (efficient weighting)**

Parameter	match 8 quarters	match 16 quarters	$\nu = 1$	$\nu = 5$
$\lambda_p$	0.0031 (0.0022)	0.0039 (0.0018)	0.0033 (0.0016)	0.0034 (0.0017)
$\kappa_p$	1.0000 ----	1.0000 ----	1.0000 ----	1.0000 ----
$\lambda_w$	0.0181 (0.0118)	0.0164 (0.0099)	0.0425 (0.0281)	0.0097 (0.0058)
$\kappa_w$	1.0000 ----	1.0000 ----	1.0000 ----	1.0000 ----
$\chi$	0.0622 (0.0467)	0.0735 (0.0395)	0.0723 (0.0449)	0.0653 (0.0453)
$\varphi$	0.6302 (0.1774)	0.6627 (0.1576)	0.6772 (0.1648)	0.6348 (0.1578)
$\sigma$	3.2413 (1.1218)	3.6928 (1.1694)	3.7168 (1.1790)	3.6092 (1.1554)
$\gamma$	0.1795 (0.2803)	0.1019 (0.2929)	0.1261 (0.2868)	0.1192 (0.2905)

**Table 3: Estimates and distance metric tests for restricted models**

Parameter	$\gamma = 0$	$\gamma = 1$	$\varphi = 0$	$\chi = 0$
$\lambda_p$	0.0033 (0.0016)	0.0012 (0.0010)	5.1861 (3.8438)	0.0015 (0.0007)
$\kappa_p$	1.0000 ----	1.0000 ----	0.0000 ----	1.0000 ----
$\lambda_w$	0.0158 (0.0100)	0.0283 (0.0155)	0.0005 (0.0004)	0.0176 (0.0098)
$\kappa_w$	1.0000 ----	1.0000 ----	0.0000 ----	1.0000 ----
$\chi$	0.0676 (0.0446)	0.0000 ----	0.0000 ----	
$\varphi$	0.6442 (0.1560)	0.5658 (0.1226)		0.4358 (0.0860)
$\sigma$	3.6861 (1.1649)	16.0261 (117.4123)	4.6993 (1.6805)	5.3823 (1.8252)
$\gamma$			0.0000 ----	0.0437 (0.3245)
loss function	31.28	43.80	190.05	32.85
test statistic	0.29	12.81	159.06	1.86
p-value	0.5932	0.0003	0.0000	0.1729

Figure 1: Empirical Characterization of Monetary Policy Transmission

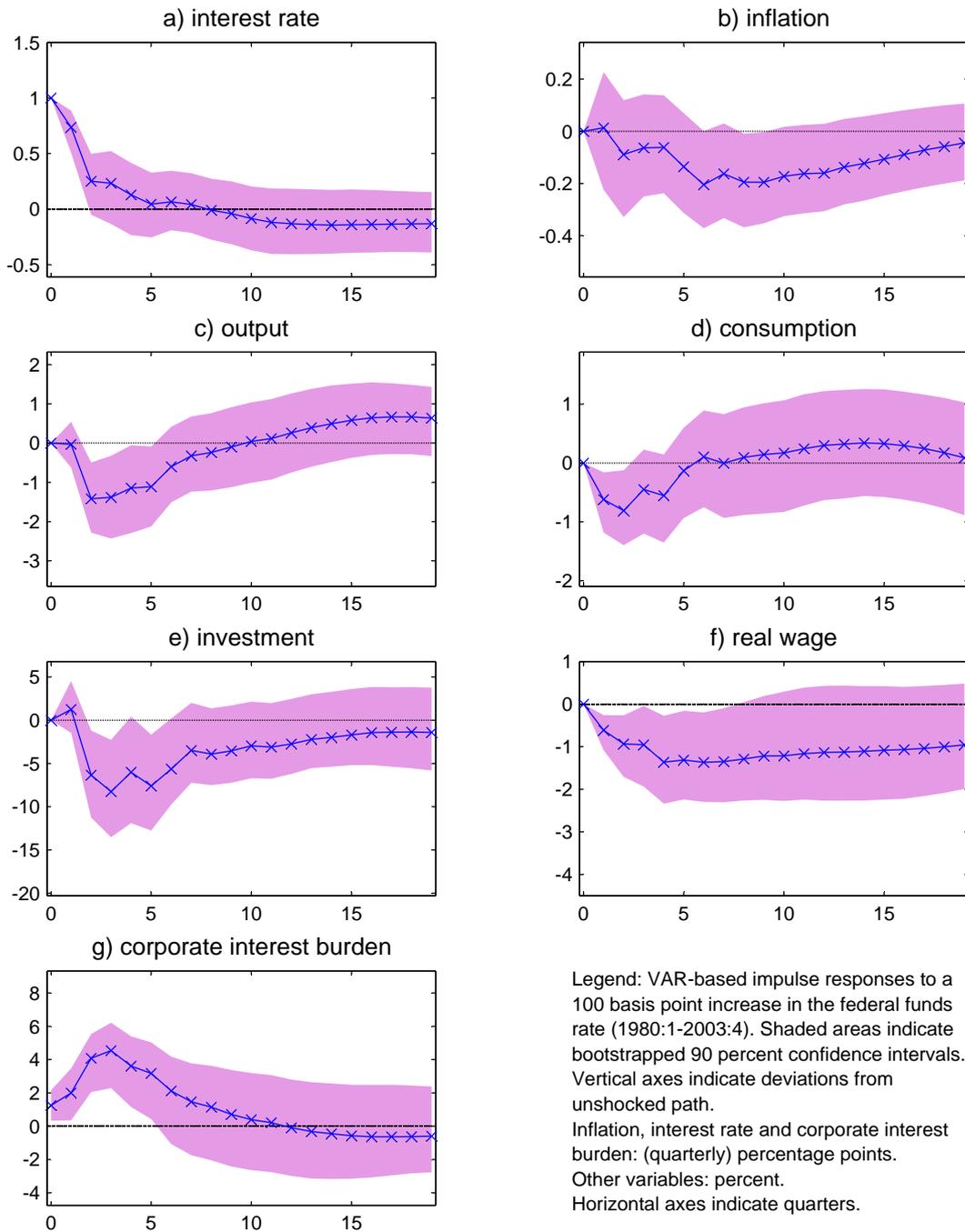
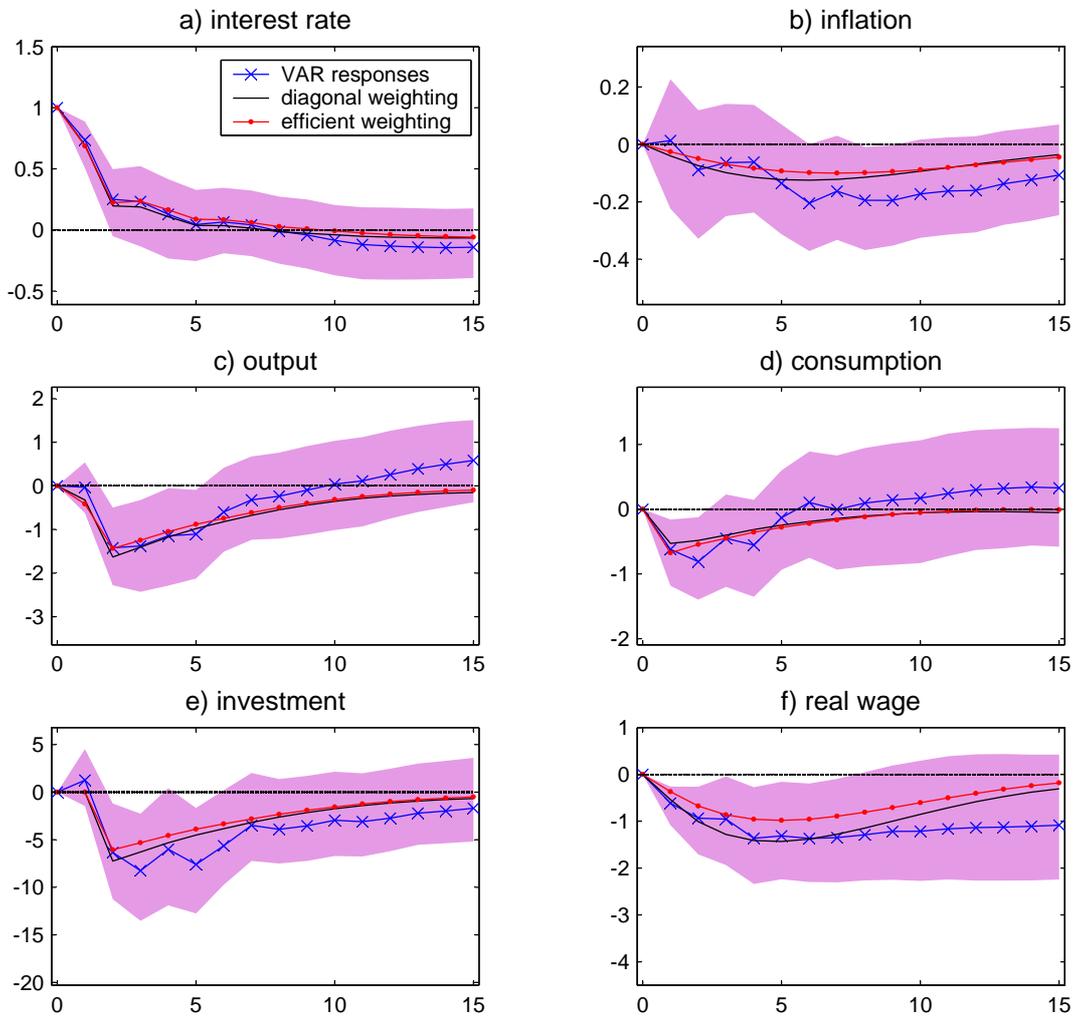
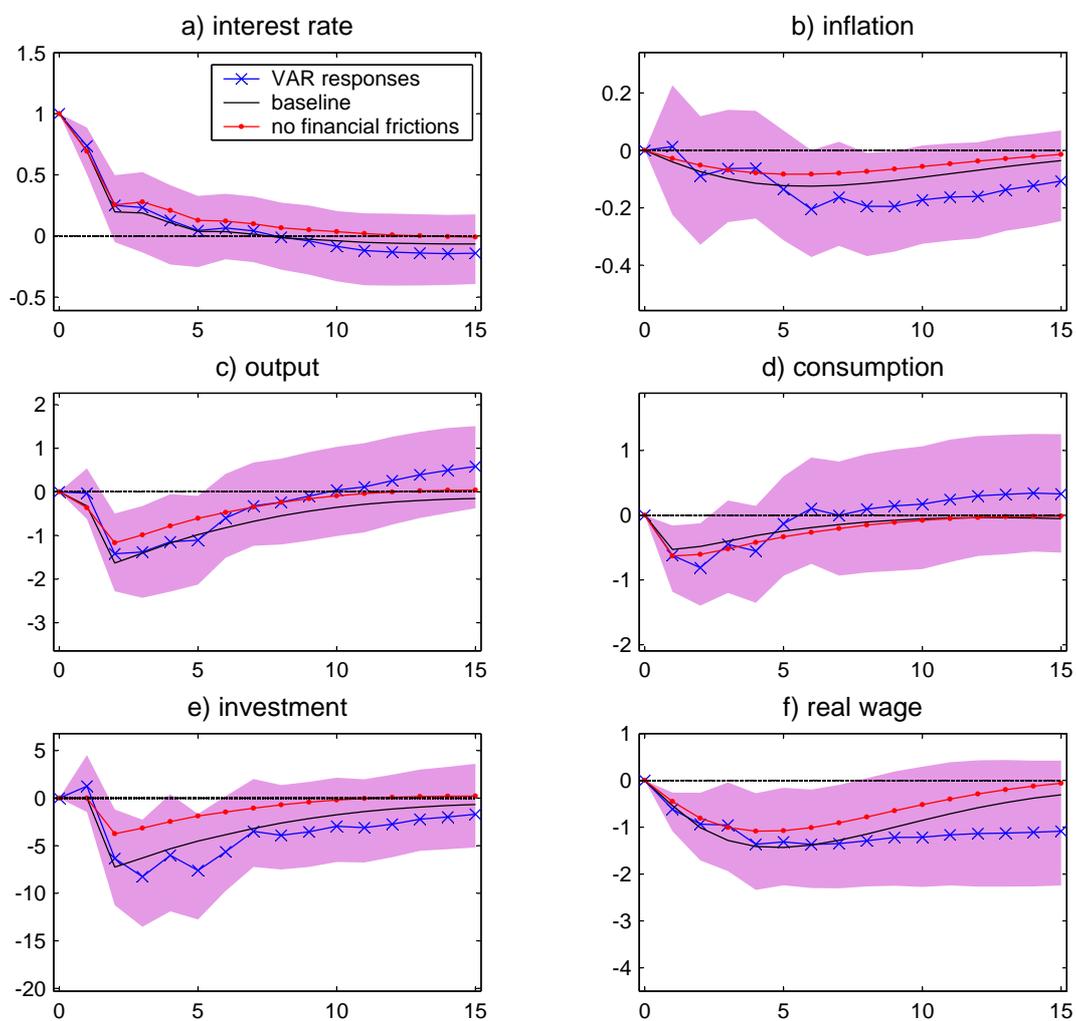


Figure 2: Impulse responses of estimated VAR and DSGE model



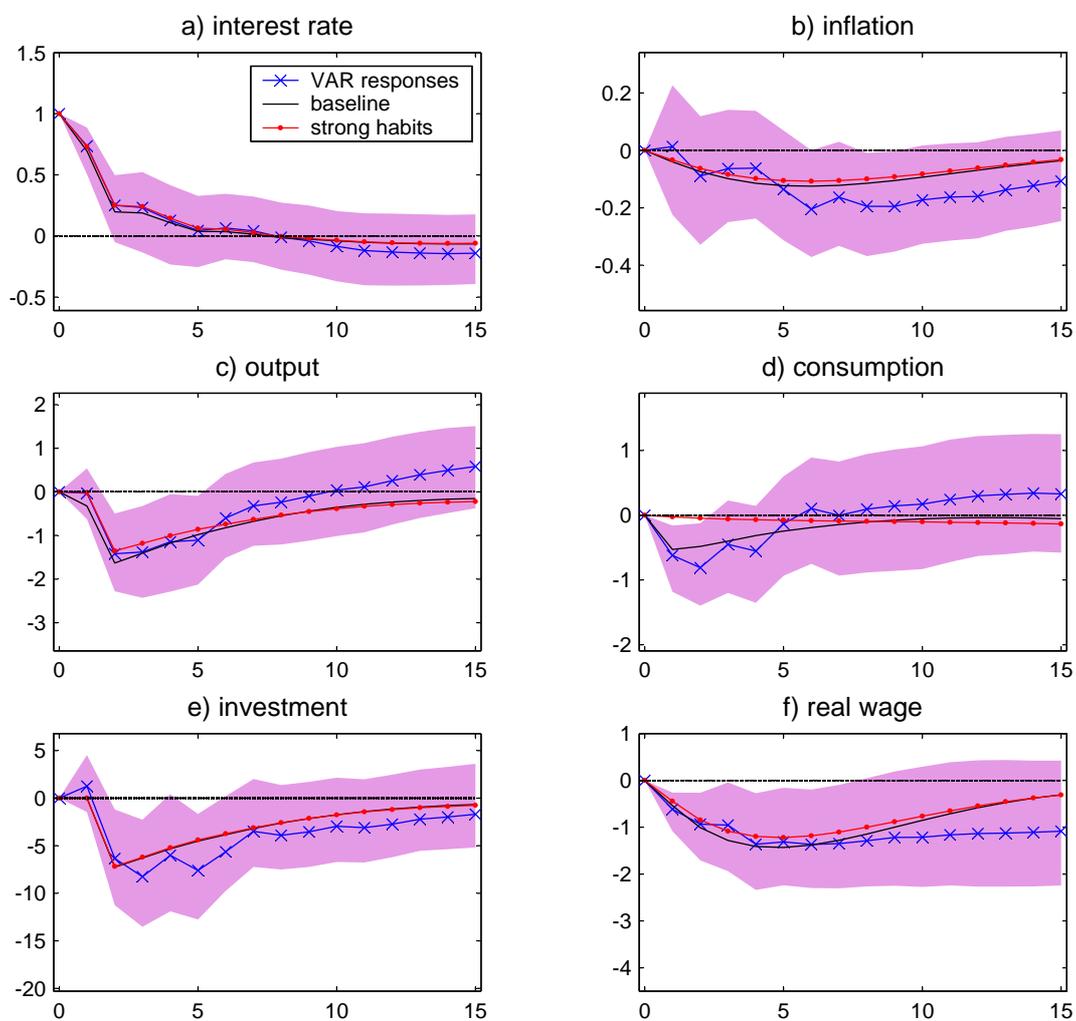
Legend: Impulse responses to a 100 basis point increase in the federal funds rate in VAR and estimated DSGE model (see legend of figure 1). Responses of estimated DSGE model differ according to the weighting matrix employed as discussed in the main text.

Figure 3: The Role of Financial Frictions



Legend: Impulse responses to a 100 basis point increase in the federal funds rate according to VAR and DSGE model. Baseline: model responses computed for parameter estimates obtained on the basis of diagonal weighting. No financial frictions:  $\chi$  set to zero, other parameters unchanged.

Figure 4: The Role of Habits



Legend: Impulse responses to a 100 basis point increase in the federal funds rate according to VAR and DSGE model. Baseline: model responses computed for parameter estimates obtained on the basis of diagonal weighting. Strong habits:  $\gamma$  set to one, other parameters unchanged.

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