The Limited Power of Monetary Policy in a Pandemic*

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June 18, 2021

Abstract

We embed an extension of the canonical epidemiology model in a New Keynesian model and analyze the role of monetary policy as a virus spreads and triggers a sizable recession. In our framework, consumption is less sensitive to real interest changes in a pandemic than in normal times because individuals have to balance the benefits of taking advantage of intertemporal substitution opportunities with the risk of becoming sick. Accommodative monetary policies such as forward guidance have only limited effects on real economic activity at the height of the pandemic. However, these policies can help sustain the recovery once the virus starts to dissipate. From a welfare standpoint, an easing of monetary policy conditions during a pandemic is not desirable since, although the economy is mired in a deep recession, the level of economic activity in the decentralized equilibrium is too high rather than too low.

JEL Classification: E5, E1, E11

Keywords: COVID-19, SIR macro model, state-dependent effects of monetary policy, forward guidance, optimal policy.

*We thank Florin Bilbiie, Hess Chung, Etienne Gagnon, Sewon Hur, Taisuke Nakata, Giovanni Nicoló, Matthias Paustian, John Roberts, Jordan Roulleau-Pasdeloup, Jae Sim, and seminar participants at the Federal Reserve Board, the Fed System Macro Meetings and the Climate Change, Pandemics, Monetary Policy conference for their comments and suggestions. The views expressed in this paper are solely the responsibility of the authors and should not be interpreted as reflecting the views of the Board of Governors of the Federal Reserve System.

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1. Introduction

The COVID-19 pandemic has been a shock of unprecedented size and nature, which has translated into new challenges for policymakers. A key feature of the crisis was the interdependency between virus dynamics and economic outcomes. As the virus spread, governments enacted restrictive measures and individuals drastically cut back on social activities. While necessary to keep the pandemic under control, these measures caused tremendous economic damage. For example, in the United States, the unemployment rate reached a post-World War II high of 14.8 percent in April 2020.

In the face of the contraction in economic activity, central banks around the world acted swiftly and forcefully by deploying a wide array of tools. In addition to interest-rate cuts, central bankers relied on forward guidance and asset purchases — staples of the monetary policy toolkit since the Great Financial Crisis —, and introduced ambitious new programs aimed at stabilizing financial markets and avoiding the disruption of the flow of credit to households and businesses (English, Forbes and Ubide, 2021).

In this paper, we develop a framework where economic decisions and virus dynamics are interlinked and analyze the role played during a pandemic by two monetary policy tools: conventional interest rate policy and forward guidance. In particular, we ask two interrelated questions. First, given the particular environment brought about by the COVID-19 pandemic, should we expect the transmission mechanism of monetary policy to be the same as in normal times? Second, is accommodative monetary policy desirable in this environment?

To address these questions, we embed an extension of the classic SIR (Susceptible, Infected, Recovered) epidemiology model in a standard New Keynesian model. On the firm side, monopolistic firms face price adjustment costs, which gives rise to a Phillips curve relating firms' markup to inflation and gives monetary policy some leverage over real activity. The novelty lies in the interaction between household decisions and virus dynamics. Notably, the transition probability from being healthy (susceptible) to sick (infected) depends on households' consumption and labor supply decisions. Therefore, susceptible individuals cut back voluntarily on consumption and hours worked when the risk of infection becomes too large. This feature implies that, even in the absence of government interventions, the economy experiences a large drop in output as the epidemic progresses. The model economy converges to the standard New Keynesian model à la Galí (2008) in the long run when the effects of the virus dissipate.

In standard models used for monetary policy analysis, monetary policy transmits exclusively through the intertemporal substitution channel: in response to a drop in the real interest rate, the returns to savings decrease and households want to consume more today. In our model, increasing one's consumption increases the probability of becoming infected and individuals therefore have to strike a balance between the willingness to consume and the desire to avoid infection, an effect we call the *consumption-versus-health-risk* motive. By that logic, in response to a decline in the real interest rate, households weigh the benefits of taking advantage of intertemporal substitution opportunities against the heightened risk of infection. As a result, the intertemporal substitution channel is partly impaired and households' consumption is less sensitive to real interest rate changes than in normal times. The importance of the consumption-versus-health-risk motive and, therefore, the extent to which monetary policy is less powerful than in normal times depends on the state of the pandemic. At the onset of the pandemic, or after its peak, when the risk of infection is limited, the effectiveness of monetary policy is close to that in normal times. However, at the height of the pandemic, when the risk of infection is maximal, monetary policy has only limited effects on real economic activity.

The feedback between economic activity and infection dynamics also generates persistence in the effects of monetary policy. Initially, an easing of monetary policy provides a boost to economic activity. However, the increase in economic activity necessarily requires an increase in social interactions, which in turn leads to a rise in infections. In subsequent periods, the economy is left with a larger stock of infected individuals, which depresses demand through the consumption-versus-health-risk motive: with the perceived risk of infection being now higher, susceptible individuals decide to postpone consumption until the epidemiological situation improves. Thus, the monetary authority faces a dynamic trade-off: any attempt to support aggregate demand today results in lower aggregate demand tomorrow.

To illustrate the quantitative relevance of these mechanisms, we examine the effects of delaying lift-off from the effective lower bound on nominal interest rates by two quarters in a calibrated version of our model. Under perfect foresight, the more accommodative stance of monetary policy cushions the initial decline in economic activity in the early stages of the pandemic. However, at the height of the pandemic, forward guidance is unsuccessful at softening the magnitude of the trough in output. This arises for two reasons: *i)* forward guidance is ineffective at propping up economic activity when the risk of infection is high; and *ii)* policy interventions early in the pandemic lead to an additional build-up in infections that depresses demand compared to the baseline economy. Once the worst of the pandemic is over and the effects of the virus start to dissipate, forward guidance helps accelerate the recovery in economic activity.

The preceding analysis suggests that the very nature of the COVID-19 shock implies that the problem faced by the monetary authority is non trivial. On the one hand, the central bank can intervene to limit the extent of the economic damage, although with decreased efficacy. On the other hand, doing so results in additional infections, which is costly from a human standpoint. A comparison of the decentralized equilibrium with the allocation that a planner would achieve reveals that the main inefficiency arising in the decentralized equilibrium stems from the fact that infected individuals do not internalize the effects of their actions on the dynamics of the epidemic. In other words, infected individuals consume and work too much. This has two implications for monetary policy. First, since it affects the consumption of all individuals in a similar way, monetary policy is not particularly effective at addressing the infection externality. Second, in the absence of policies targeted directly at infected individuals, the overall level of economic activity is too high. As a consequence, policies aimed at stimulating economic activity are not desirable from a welfare standpoint.

Our paper is related to the literature on the macroeconomic implications of the COVID-19 health crisis. This literature is too vast to be concisely summarized here. Instead, we point the reader to studies that are close to ours in terms of focus and modeling choices. Several authors starting with Eichenbaum, Rebelo and Trabandt (2021) have modified the standard SIR model to introduce a feedback between individuals' economic decisions and epidemic dynamics and have embedded such an extended framework in macroeconomic models. Eichenbaum, Rebelo and Trabandt (2021) and Jones, Philippon and Venkateswaran (2020) study the trade-off between public health objectives and the economic costs of the pandemic. Using a rich heterogeneous agent model, Kaplan, Moll and Violante (2020) emphasize that the trade-off is not only between lives and livelihoods, but also over who should bear the burden of the economic costs. Bodenstein, Corsetti and Guerrieri (2020) show instead that social distancing measures may improve economic outcomes, as an unchecked epidemic could incapacitate core sectors and result in a steep fall in economic activity.

Levin and Sinha (2020) and Woodford (2020) are the two papers closest to ours. Both papers examine the role of monetary policy in the face of the COVID-19 shock. Levin and Sinha (2020) stress that several issues such as the myopia of economic agents or limited commitment by the central bank may be especially relevant in the current environment, thereby weakening the power of forward guidance. While we share their conclusion that monetary policy may be less effective in a pandemic than in normal times, our argument rests instead on the observation that households' consumption behavior changes as the virus spreads. Woodford (2020) argues that monetary policy is ineffective at restoring the first-best allocation when the effects of a shock are sectorally concentrated. In his framework, the disruption of the circular flow of payments brought about by the initial shock leads to cascading effects across sectors. In that case, an interest-rate cut is not desirable since, although it can stimulate aggregate demand, it fails to stimulate demand of the right sorts. We reach similar conclusions for different reasons. In our model, monetary policy is also poorly equipped to address the inefficiencies arising in the decentralizing equilibrium since it cannot target infected individuals directly. Moreover, in the absence of such targeted tools, the overall level of economic activity in the decentralized equilibrium is too high, implying that additional stimulus in the form of interest-rate cuts is not desirable.

Our paper is also related to the literature on the "forward guidance puzzle" (Negro, Giannoni and Patterson, 2015) – the observation that forward guidance policies have unrealistically powerful effects in standard New Keynesian models (Eggertsson and Woodford, 2003, Calstrom, Fuerst and Paustian, 2015). Different rationalizations to this puzzle based, for example, on departures from the rational expectations hypothesis (Woodford, 2018, Angeletos and Lian, 2018, Fahri and Werning, 2019, Gabaix, 2020), sticky information (Chung, Herbst and Kiley, 2015, Kiley, 2016), incomplete markets (McKay, Nakamura and Steinsson, 2016, Werning, 2015, Bilbiie, 2019, Bilbiie, 2020, Hagedorn et al., 2019, Ferrante and Paustian, 2019), wealth in the utility function (Michaillat and Saez, 2019), or the presence of durable goods (McKay and Wieland, 2020) have been proposed in the literature. For the reasons outlined above, in our model, forward guidance loses much of its power in a pandemic.

Finally, several recent studies have argued that the effects of monetary policy may be state-dependent. In Berger et al. (2018) and Eichenbaum, Rebelo and Wong (2018), the state dependency stems from the presence of fixed-rate mortgages. In McKay and Wieland (2020), the state dependency is related to the distribution of durable expenditures relative to adjustment thresholds. In our paper, the state dependency is linked to individuals' behavioral response to the diffusion of the virus and depends on the stock of infected individuals in the population.

The paper is organized as follows. Section 2 describes the model. Section 3 calibrates the model, simulates a pandemic of moderate size, and examines its consequences on economic activity. Section 4 performs several monetary policy exercises and shows that the effects of monetary policy are weaker in a pandemic than in normal times. Section 5 analyzes whether accommodative monetary policy is desirable in a pandemic. Section 6 examines the sensitivity of our results to reasonable parameter variations. Section 7 concludes.

2. Model

Our model economy is populated by: *(i)* households who are subject to the evolution of a pandemic; *(ii)* monopolistically competitive firms facing price adjustment costs; and *(iii)* a central bank conducting monetary policy subject to the effective lower bound on nominal interest rates. The frequency of our model economy is weekly. In this section, we first describe the epidemiological model and then overview the macroeconomic side of the model[1].

2.1. Epidemics: The extended SIR model

We consider a SIR (Susceptible, Infected, Recovered) model with the possibility of death. In the standard SIR model (Kermarck and McKendrick, 1927), transitions between different health status are exogenous. However, in reality, individuals may be able to reduce the probability of becoming infected by cutting down on activities that involve interacting with others, such as the purchase of consumption goods and work. Thus, following Eichenbaum, Rebelo and Trabandt (2021), we extend the SIR model by assuming that the transition probability from being healthy (susceptible) to sick (infected) depends on people's economic decisions.

Once the epidemic starts, individuals are divided in three groups: *(i)* susceptible individuals, S_t, who have not yet been exposed to the disease; *(ii)* infected individuals, I_t, who have contracted the disease; and *(iii)* recovered individuals, R_t, who have survived and acquired immunity. We assume that both symptomatic and asymptomatic individuals are equally infectious, that everyone is equally susceptible to contagion, and that recovered individuals have long-lasting immunity[2]. A susceptible person can contract the virus only through contact with an already infected person and infected people remain infectious until they recover or die. We also assume that individuals know their health status.

[1] Our model is similar to the New Keynesian model developed by Eichenbaum, Rebelo and Trabandt (2020). Unlike these authors, we do not include physical capital and government spending but enforce the effective lower bound on nominal interest rates.

[2] There is no consensus in the medical and scientific communities about the duration of immunity. We acknowledge assuming long-lasting, perpetual in our case, immunity after recovering from the disease is a simplifying assumption.

The number of newly infected people T_t is given by

$$T_t = \pi_{s1} S_t C_{s,t} I_t C_{i,t} + \pi_{s2} S_t N_{s,t} I_t N_{i,t} + \pi_{s3} S_t I_t, \tag{1}$$

where S_t is the number of susceptible individuals, I_t is the number of infected individuals, R_t is the number of recovered individuals, and $C_{k,t}$ and $N_{k,t}$ are the consumption and hours worked by individuals of type k, where $k = S, I, R$. The technological parameters π_{s1} and π_{s2} denote the probability of contracting the virus while purchasing consumption goods and supplying hours of work, respectively. The parameter π_{s3} captures both how likely one is to become infected in random interactions and the intensity of these interactions.[3] We assume that the probability of being infected through more than one channel is zero.

The number of susceptible people at time $t+1$ is the number of susceptible people at time t minus the number of newly infected people at time t, T_t,

$$S_{t+1} = S_t - T_t. \tag{2}$$

Let π_r be the per-period probability of recovering after being infected and π_d be the per-period probability of dying if infected. The number of infected people at time $t+1$ is equal to the number of infected people at time t plus the number of newly infected, T_t, minus the number of infected people who either recovered, $\pi_r I_t$, or died, $\pi_d I_t$,

$$I_{t+1} = I_t + T_t - (\pi_r + \pi_d) I_t. \tag{3}$$

The number of recovered people at time $t+1$ is the number of recovered people at time t plus the number of infected people who just recovered, $\pi_r I_t$,

$$R_{t+1} = R_t + \pi_r I_t. \tag{4}$$

The number of deaths at time $t+1$ is the number of deaths at time t plus the number of infected individuals who just died, $\pi_d I_t$,

$$D_{t+1} = D_t + \pi_d I_t. \tag{5}$$

The basic reproduction number, $\mathcal{R}_0$, is a useful statistic to summarize the transmissibility of a virus and, hence, quantify the potential intensity of an outbreak. $\mathcal{R}_0$ is defined as the number of new infections generated by the first ill person in a population where everyone is susceptible. A large $\mathcal{R}_0$ implies a rapid spread of the virus. In the standard SIR model, where the probability of getting sick is exogenous and constant, $\mathcal{R}_0$ is also constant over time. In our model, however, individuals can reduce the probability of becoming infected by cutting down on consumption and hours worked, which implies a time-varying $\mathcal{R}_{0,t}$. The basic reproduction number in our model is given by

$$\mathcal{R}_{0,t} = \frac{\pi_{s1} C_{s,t} C_{i,t} + \pi_{s2} N_{s,t} N_{i,t} + \pi_{s3}}{\pi_r + \pi_d}, \tag{6}$$

[3] Note that in the standard SIR model $\pi_{s1} = \pi_{s2} = 0$.

where the numerator captures the transmission rate and the denominator summarizes the recovery and fatality rates.

After rearranging equation 3, we can express the dynamics of infections as a function of $\mathcal{R}_{0,t}$,

$$\frac{I_{t+1} - I_t}{I_t} = (\pi_r + \pi_d)\left(\mathcal{R}_{0,t} S_t - 1\right). \tag{7}$$

This equation states that the number of infected people grows when the *effective* reproduction number, $\mathcal{R}_{0,t} S_t$, is larger than one, and subsides when it is lower than one. For a given $\mathcal{R}_{0,t}$, the virus dies out naturally as S_t decreases and society reaches herd immunity. Alternatively, the spread of the virus may be halted temporarily or permanently if voluntary or government-induced changes in individual behavior are effective in reducing $\mathcal{R}_{0,t}$.

2.2. Households

The economy is populated by a continuum of households of measure one. Households are of size one and the momentary utility function of household members is given by

$$u(c_t, n_t) = \frac{c_t^{1-\sigma}}{1-\sigma} - \chi \frac{n_t^{1+1/\varphi}}{1+1/\varphi} + \bar{u}, \tag{8}$$

where $1/\sigma$ is the elasticity of intertemporal substitution, φ is the Frisch elasticity of labor supply, and $\bar{u}$ is a flow value of being alive. The consumption level c_t is a Dixit-Stiglitz aggregator of the different varieties of goods produced by firms, $c_t \equiv \left[\int_0^1 c_t(j)^{\frac{\theta-1}{\theta}} dj\right]^{\frac{\theta}{\theta-1}}$, where θ is the elasticity of substitution between varieties and $c_t(j)$ is the consumption of goods produced by firm j. The optimal allocation of income to each variety is given by $c_t(j) = \left[\frac{P_t(j)}{P_t}\right]^{-\theta} c_t$, where $P_t = \left[\int_0^1 P_t(j)^{\frac{\theta-1}{\theta}} dj\right]^{\frac{\theta}{\theta-1}}$ is the aggregate price index and $P_t(j)$ is the price of variety j.

Initially, all household members are susceptible to the disease. Once the epidemic starts, household members can be either susceptible, infected, or recovered. The head of the household makes decisions on behalf of all household members. She maximizes the intertemporal welfare of household members using a utilitarian welfare criterion (identical weights for all members). At the beginning of the period, the head of the household pools resources and determines the consumption/saving and labor supply choices for each type of member, implementing symmetric choices for all individuals of a given type. This setup implies that individuals are insured against the income risk associated with transitioning between health states. Moreover, the head of the household is aware of the infection technology described by equation 1, but does not internalize the impact of her choices on economy-wide infection rates. Thus, from the household perspective, the per-period probability of infection of its susceptible members is given by

$$\tau_t = \pi_{s1} c_{s,t} \left(I_t C_{i,t}\right) + \pi_{s2} n_{s,t} \left(I_t N_{i,t}\right) + \pi_{s3} I_t, \tag{9}$$

where we denote household-level variables with lower-case letters and economy-wide variables with upper-case letters. Households have access to one-period nominal government bonds that promise a given nominal return tomorrow, R_t^{mp}, and they receive firm dividends, Υ_t, in the form of lump-sum payments.

The optimization program of the head of the household is given by:

$$V(s_t, i_t, r_t, b_t) = \max_{c_{s,t}, c_{i,t}, c_{r,t}, n_{s,t}, n_{i,t}, n_{r,t}, b_{t+1}} \{s_t u(c_{s,t}, n_{s,t}) + i_t u(c_{i,t}, n_{i,t}) + r_t u(c_{r,t}, n_{r,t}) + \beta V(s_{t+1}, i_{t+1}, r_{t+1}, b_{t+1})\} \quad (10)$$

subject to

$$s_t c_{s,t} + i_t c_{i,t} + r_t c_{r,t} + b_{t+1} = \frac{1 + R_{t-1}^{mp}}{\Pi_t} b_t + w_t (s_t \phi_s n_{s,t} + i_t \phi_i n_{i,t} + r_t \phi_r n_{r,t}) + \Upsilon_t \quad (11)$$

$$s_{t+1} = (1 - \tau_t (c_{s,t}, n_{s,t})) s_t \quad (12)$$

$$i_{t+1} = (1 - \pi_r - \pi_d) i_t + \tau (c_{s,t}, n_{s,t}) s_t \quad (13)$$

$$r_{t+1} = r_t + \pi_r i_t \quad (14)$$

where b_t is the real value of bonds, R_t^{mp} is the nominal interest rate, Π_t is the current gross inflation rate, ϕ_k is the labor productivity of type k households, and w_t is the wage per efficient hour. The notation $\tau(c_{s,t}, n_{s,t})$ makes it explicit that, from the household's perspective, the probability of infection only depends on the consumption and hours choices of susceptible individuals.

Let λ_t be the Lagrange multiplier associated with the budget constraint. The marginal utility of consumption for susceptible members, infected members, and recovered members is given, respectively, by

$$u_c(c_{s,t}, n_{s,t}) + \beta \frac{\partial \tau (c_{s,t}, n_{s,t})}{\partial c_{s,t}} (V_{i,t+1} - V_{s,t+1}) = \lambda_t, \quad (15)$$

$$u_c(c_{i,t}, n_{i,t}) = \lambda_t, \quad (16)$$

$$u_c(c_{r,t}, n_{r,t}) = \lambda_t. \quad (17)$$

Similarly, the labor supply condition for each type of household member is

$$u_n(c_{s,t}, n_{s,t}) + \beta \frac{\partial \tau (c_{s,t}, n_{s,t})}{\partial n_{s,t}} (V_{i,t+1} - V_{s,t+1}) = -\lambda_t w_t \phi_s, \quad (18)$$

$$u_n(c_{i,t}, n_{i,t}) = -\lambda_t w_t \phi_i, \quad (19)$$

$$u_n(c_{r,t}, n_{r,t}) = -\lambda_t w_t \phi_r. \quad (20)$$

The Euler equation for bonds is

$$\lambda_t = \beta \lambda_{t+1} \frac{1 + R_t^{mp}}{\Pi_{t+1}}. \quad (21)$$

Finally, the envelope conditions with respect to health status are

$$V_{s,t} = u(c_{s,t}, n_{s,t}) + \lambda_t (w_t \phi_s n_{s,t} - c_{s,t}) + (1 - \tau(c_{s,t}, n_{s,t})) \beta V_{s,t+1} + \tau(c_{s,t}, n_{s,t}) \beta V_{i,t+1}, \tag{22}$$

$$V_{i,t} = u(c_{i,t}, n_{i,t}) + \lambda_t (w_t \phi_i n_{i,t} - c_{i,t}) + (1 - \pi_r - \pi_d) \beta V_{i,t+1} + \pi_r \beta V_{r,t+1}, \tag{23}$$

$$V_{r,t} = u(c_{r,t}, n_{r,t}) + \lambda_t (w_t \phi_r n_{r,t} - c_{r,t}) + \beta V_{r,t+1}. \tag{24}$$

We explore next the role played by the virus in the labor supply and consumption decisions of susceptible household members. We first combine equations 15 and 18 to obtain the following expression for their labor supply

$$w_t \phi_s = \frac{\chi n_{s,t}^{1/\varphi} - \beta \frac{\partial \tau(c_{s,t}, n_{s,t})}{\partial n_{s,t}} (V_{i,t+1} - V_{s,t+1})}{c_{s,t}^{-\sigma} + \beta \frac{\partial \tau(c_{s,t}, n_{s,t})}{\partial c_{s,t}} (V_{i,t+1} - V_{s,t+1})}. \tag{25}$$

Equation 25 equates the hourly wage with the marginal rate of substitution between hours worked and consumption. The marginal disutility of labor, the numerator in equation 25, includes an additional term compared to the case without a pandemic, $\left[-\beta \frac{\partial \tau(c_{s,t}, n_{s,t})}{\partial n_{s,t}} (V_{i,t+1} - V_{s,t+1})\right]$. By working longer hours, individuals have higher chances of becoming infected, that is $\partial \tau(c_{s,t}, n_{s,t}) / \partial n_{s,t} > 0$, and, in case of infection, they suffer a loss in lifetime utility since $(V_{i,t+1} - V_{s,t+1}) < 0$. Thus, as the pandemic progresses through the population, susceptible household members willingly cut back on hours worked. Similarly, the marginal utility of consumption, the denominator in equation 25, depends on the probability that individuals will become infected through consumption activities, $\left[\beta \frac{\partial \tau(c_{s,t}, n_{s,t})}{\partial c_{s,t}} (V_{i,t+1} - V_{s,t+1})\right]$.

Second, we combine equations 15 and 21 to obtain the following Euler equation for susceptible household members

$$c_{s,t}^{-\sigma} + \overbrace{\beta \frac{\partial \tau(c_{s,t}, n_{s,t})}{\partial c_{s,t}} (V_{i,t+1} - V_{s,t+1})}^{\text{consumption vs. health risk}} = \beta \frac{1 + R_t^{mp}}{\Pi_{t+1}} \left(c_{s,t+1}^{-\sigma} + \overbrace{\beta \frac{\partial \tau(c_{s,t+1}, n_{s,t+1})}{\partial c_{s,t+1}} (V_{i,t+2} - V_{s,t+2})}^{\text{consumption vs. health risk}} \right). \tag{26}$$

Equation 26 includes a new motive that we label as the *consumption-versus-health-risk* motive. As in the case of the labor supply choice, consuming more exposes susceptible individuals to a greater risk of infection, that is $\partial \tau(c_{s,t}, n_{s,t}) / \partial c_{s,t} > 0$, which in turn may result in a loss in lifetime utility since $(V_{i,t+1} - V_{s,t+1}) < 0$. Thus, susceptible individuals factor in the risk of infection when deciding on their intertemporal consumption allocation. In particular, they prefer to consume more when the risk of infection is low. The optimal consumption pattern is a function of the state of the pandemic: if the outlook for the virus is about to improve (worsen), susceptible household members prefer to delay (increase) consumption.

In contrast, since infected and recovered individuals are no longer exposed to the risk of infection, the consumption-versus-health-risk motive is not present in their respective Euler equations

$$u_c\left(c_{i,t}, n_{i,t}\right) = \beta\frac{1+R_t^{mp}}{\Pi_{t+1}}u_c\left(c_{i,t+1}, n_{i,t+1}\right), \tag{27}$$
$$u_c\left(c_{r,t}, n_{r,t}\right) = \beta\frac{1+R_t^{mp}}{\Pi_{t+1}}u_c\left(c_{r,t+1}, n_{r,t+1}\right). \tag{28}$$

2.3. Firms

A continuum of monopolistic firms, indexed by j, produce differentiated goods according to a linear technology

$$Y_t(j) = A\left[S_t\phi_s N_{s,t}(j) + I_t\phi_i N_{i,t}(j) + R_t\phi_r N_{r,t}(j)\right], \tag{29}$$

where A is the (constant) level of technology. Firms face quadratic price adjustment costs

$$\Phi_t(j) = \frac{\phi^p}{2}\left(\frac{P_t(j)}{P_{t-1}(j)} - \Pi^*\right)^2 Y_t, \tag{30}$$

where Π^* is the inflation target of the monetary authority. These costs have the same composition as the aggregate consumption basket and are proportional to aggregate output. Firms are controlled by a risk-neutral manager who discounts future profits at rate β. Firms choose the price $P_t(j)$ to maximize the expected discounted sum of future profits

$$V_t^p\left(P_{t-1}(j)\right) = max_{P_t(j)}\left\{\frac{P_t(j)}{P_t}Y_t(j) - \frac{w_t}{A}Y_t(j) - \frac{\phi^p}{2}\left(\frac{P_t(j)}{P_{t-1}(j)} - \Pi^*\right)^2 Y_t + \beta V_{t+1}^p\left(P_t(j)\right)\right\}, \tag{31}$$

subject to the demand for their variety $Y_t(j) = \left(\frac{P_t(j)}{P_t}\right)^{-\theta} Y_t^d$, where Y_t^d is aggregate demand. In equilibrium, all firms face a similar problem and choose the same price, which implies that $Y_t = \int_0^1 Y_t(j)dj = Y_t^d$. The Phillips curve is given by

$$1 - \theta + \theta\frac{w_t}{A} - \phi^p\Pi_t\left(\Pi_t - \Pi^*\right) + \beta\phi^p\Pi_{t+1}\left(\Pi_{t+1} - \Pi^*\right)\frac{Y_{t+1}}{Y_t} = 0. \tag{32}$$

2.4. Monetary policy

The monetary authority sets the short-term nominal interest rate using the following rule

$$1 + R_t^{mp} = max\left\{(1+R^{mp})\left[\left(\frac{\Pi_t}{\Pi^*}\right)^{\delta_\pi}\left(\frac{Y_t}{Y}\right)^{\delta_y}\right], 1 + R_{min}^{mp}\right\}, \tag{33}$$

where the absence of time subscript denotes steady-state values and the max operator captures the presence of the effective lower bound, fixed at R_{min}^{mp}.

2.5. Equilibrium

In equilibrium, the fraction of household members who are susceptible, infected, and recovered is the same as the corresponding fraction in the population. Therefore, $s_t = S_t$, $i_t = I_t$, and $r_t = R_t$. Moreover, all households implement symmetric consumption and labor choices for individuals of the same type. Therefore, $c_{s,t} = C_{s,t}$, $c_{i,t} = C_{i,t}$, $c_{r,t} = C_{r,t}$, $n_{s,t} = N_{s,t}$, $n_{i,t} = N_{i,t}$, and $n_{r,t} = N_{r,t}$. Aggregate consumption is a weighted average of the consumption of each type

$$C_t = S_t C_{s,t} + I_t C_{i,t} + R_t C_{r,t}. \tag{34}$$

Firm dividends are given by

$$\Upsilon_t = (A - w_t)\left(\phi S_t N_{s,t} + \phi_i I_t N_{i,t} + \phi_r R_t N_{r,t}\right) - \frac{\phi^p}{2}\left(\Pi_t - \Pi^*\right)^2 Y_t. \tag{35}$$

In the absence of government-provided liquidity, bonds are in zero net supply. The economy-wide resource constraint is obtained by aggregating the budget constraints of households

$$C_t = A\left(1 - \frac{\phi^p}{2}\left(\Pi_t - \Pi^*\right)^2\right)\left(\phi S_t N_{s,t} + \phi_i I_t N_{i,t} + \phi_r R_t N_{r,t}\right). \tag{36}$$

3. The baseline economy

3.1. Calibration

The model is calibrated at a weekly frequency. We first discuss the calibration of the parameters of the New Keynesian side of the model. The elasticity of substitution between goods is set to $\theta = 6$, implying that price markups are equal to 20% in steady state. The inflation target and the steady-state real interest rate are equal to 2% at an annual frequency, which correspond to a weekly gross rate of $1.02^{\frac{1}{52}}$. The monetary authority responds to deviations of inflation and output from target with coefficients $\delta_\pi = 1.5$ and $\delta_y = 0.5/52$, respectively. Both the intertemporal elasticity of substitution $1/\sigma$ and the Frisch elasticity of labor supply φ are set to $1/2$, which are standard values in the literature. The discount factor is set to an annual value of 0.98 or, equivalently, a weekly value of $0.98^{1/52}$. The productivity levels of each type of household are fixed as in Eichenbaum, Rebelo and Trabandt (2021): $\phi_s = \phi_r = 1$ and $\phi_i = 0.8$. We calibrate the price adjustment cost parameter ϕ^p according to the following logic. While the current COVID-19 pandemic was an unprecedented shock to the economy, inflation remained relatively stable. Thus, we need to have a flat Phillips curve in order to prevent unrealistic price movements. In particular, we target a slope of the Phillips curve of 0.0019 at a quarterly frequency, as in the FRB/US model of the U.S. economy (Brayton, Laubach and Reifschneider, 2014), which implies a value for the price cost parameter, ϕ^p, of 34129[4]. Finally, we normalize output, hours worked, and population in the pre-pandemic steady state to

[4]To obtain this value, we conduct the following experiment. Assume that marginal cost is permanently 1% higher. In a quarterly (linearized) version of the model, this would result in a permanent $\frac{0.0019}{1-\beta^{13}}$ percent increase in inflation. We want to obtain a similar answer in our weekly model. Given that the slope of the (linearized) Phillips curve is $\frac{\theta-1}{\phi^p}$, this implies that $\frac{\theta-1}{\phi^p(1-\beta)} = \frac{0.0019}{1-\beta^{13}}$.

one. Through steady-state relationships, these assumptions allow us to pin down the parameters A and χ.

Next, we choose the parameters characterizing the SIR side of the model. Following Bar-On et al. (2020), we set the basic reproduction number, $\mathcal{R}_0$, to 2 (on the low end of a plausible range of estimates), the infection fatality rate to 0.8% (on the high end of a plausible range of estimates), and the average duration in the infected state to 15 days. Since our calibration is weekly, this implies that the fatality rate is equal to $\pi_d = 0.008 * 7/15$ and that the recovery rate is equal to $\pi_r = 7/15 - \pi_d$. As in Jones, Philippon and Venkateswaran (2020), and consistent with the evidence presented in Ferguson et al. (2020), we assume that work and consumption activities account each for 1/4 of transmissions. The flow value of life $\bar{u}$ is chosen so that the cost of death is consistent with estimates of the value of a statistical life used by government entities such as the Environmental Protection Agency (EPA). Greenstone and Nigam (2020) report that the EPA uses a 2020 value of a statistical life of \$9.9 million 2011 dollars. After accounting for income growth to 2020, they find a value of statistical life of \$11.5 million 2020 dollars[5], which corresponds to 10,310 times per capita weekly income in the United States in 2019. For simplicity, we define the value of a statistical life, VSL, based on the situation of an infinitely-lived representative individual in the pre-pandemic steady state. We have

$$VSL = \frac{\frac{\frac{c^{1-\sigma}}{1-\sigma} - \chi \frac{n^{1+1/\varphi}}{1+1/\varphi} + \bar{u}}{1-\beta}}{c^{-\sigma}} = 10310 * c, \tag{37}$$

which implies that $\bar{u}$ is equal to

$$\bar{u} = (1-\beta) * c^{1-\sigma} * 10310 - \frac{c^{1-\sigma}}{1-\sigma} + \chi \frac{n^{1+1/\varphi}}{1+1/\varphi} = 5.4. \tag{38}$$

We acknowledge that considerable uncertainty remains about the values of certain epidemiological parameters, even many months after the onset of the pandemic. For this reason, we check that our results are robust to sensible parameter variations in Section 6.

We solve the nonlinear model under the assumption of perfect foresight using Dynare's (Adjemian et al., 2011) perfect foresight solver.

3.2. The economic effects of a pandemic

In this section, we simulate a pandemic of moderate size and overview the equilibrium population and economic dynamics. We aim to generate a sensible path for the epidemic around which to conduct our monetary policy experiments. In our model economy, agents have perfect foresight and, hence, know about the new virus and how it propagates through the population. We start the simulation with an initial infection rate of $I_0 = 0.5\%$. This corresponds to a situation where agents do not become immediately aware of the extent to which the virus has propagated within the population. Once they do and adapt their behavior accordingly, the virus has already taken hold.

[5] The U.S. Department of Transportation provides an estimate for the valuation of a statistical life using a 2020 base year equal to \$11.6 million.

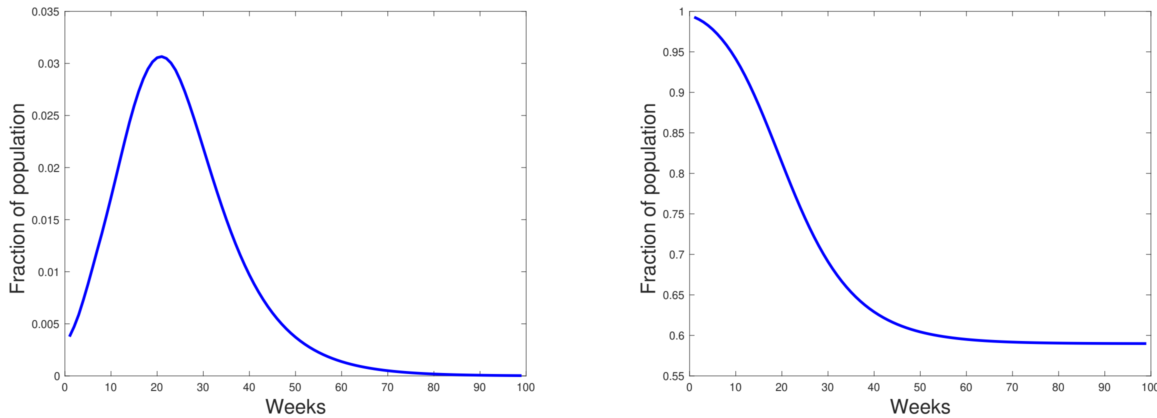
In the standard SIR model, transition probabilities between health states are exogenous. Toxvaerd (2020) shows that standard SIR models tend to overstate the size of a pandemic relative to models in which individuals' behavior affects the transition rates between different health status. A similar criticism can be applied to macro-SIR models such as Eichenbaum, Rebelo and Trabandt (2021), Jones, Philippon and Venkateswaran (2020), or ours, since, in these models, individuals can only reduce their risk exposure by cutting down on consumption and hours worked. That is, the intensity of random social interactions — interactions not involving consumption or work — is assumed to be fixed. We attempt to overcome this shortcoming by introducing shocks to the parameter governing the probability of infection through random interactions, π_{s3}. These shocks are meant to capture voluntary social distancing not linked to consumption or work and provide a sensible path for the epidemic in our model economy.

In our baseline economy, we also take into account the widespread and long-lasting shift to working from home that occurred in the first months of the pandemic. Dingel and Neiman (2020) conclude that about 37% of jobs in the United States can be performed entirely at home. Brynjolfsson et al. (2020) report that about half of those employed pre-COVID-19 were working from home in April and May 2020. In our framework, the switch to telework is best represented by shocks to the parameter capturing the probability of becoming infected through interactions at work, π_{s2}. We introduce shocks so that π_{s2} is permanently reduced by about 1/3 in the first weeks of the pandemic.

Figure 1 plots the epidemiological outcomes in our simulation. As mentioned above, we aim to generate a sensible path for the epidemic around which to conduct our monetary policy experiments. For simplicity, we decide to simulate only one wave of the pandemic: the virus rapidly spreads from the start of the simulation until week 22, where the share of infected individuals in the population reaches a peak of 3.07 percent; epidemiological outcomes gradually improve thereafter. The share of susceptible households progressively declines and remains steady around 59 percent from week 100 until the end of the simulation: only 41 percent of the population ever becomes infected, which, for a U.S. population of 330 million people, amounts to about 136.4 million Americans. Our choice for a peak infection rate of 3 percent was guided by the following logic. A version of the SIR side of our model calibrated to U.S. death data, as in Fernández-Villaverde and Jones (2020), predicts that the share of infected individuals in the population in the United States peaked at 1.7 percent in the spring of 2020 and 2.4 percent in the winter of 2020-2021. Thus, since we do not include any government-mandated restrictions in our baseline scenario, we view a peak infection rate of 3 percent as a reasonable outcome. It is also worth noting that, while our choice for the path of the pandemic was made for ease of exposition, we could easily accommodate more complicated scenarios, such as multiple waves of the pandemic. Our qualitative results would remain unaffected. In Section 6, we consider pandemics of both smaller and larger sizes.

The pandemic triggers a sizable recession in the model economy: weekly output is about 12 percent lower at the trough as shown in the upper left panel in Figure 2. Several factors are behind the drop in economic activity: *(i)* households know they can effectively reduce the probability of becoming infected by consuming and working less, and *(ii)* as households become infected, their

Figure 1. Epidemiological Effects (weekly)



(a) Infected Households (b) Susceptible Households

productivity temporarily declines so that aggregate productivity is lower during the pandemic. Once the epidemiological situation starts improving, the economy steadily recovers reaching output levels close to its post-epidemic steady state around 70 weeks after the start of the pandemic (about 48 weeks after the trough). In our model, the pandemic shows up both as a shock to aggregate demand (through the Euler equation of susceptible individuals) and as a shock to labor supply (through the labor supply condition of susceptible individuals). While the drop in demand, and the associated decrease in labor demand, puts downward pressure on wages, the shock to labor supply puts upward pressure on wages. As shown in the upper right panel in Figure 2, the labor supply effect dominates: inflation initially increases as forward-looking firms anticipate future rises in costs and start adjusting prices accordingly[6]. With inflation increasing and output declining only gradually, the policy rate reaches its effective lower bound (ELB thereafter) 14 weeks after the start of the pandemic and it remains there for 20 weeks.

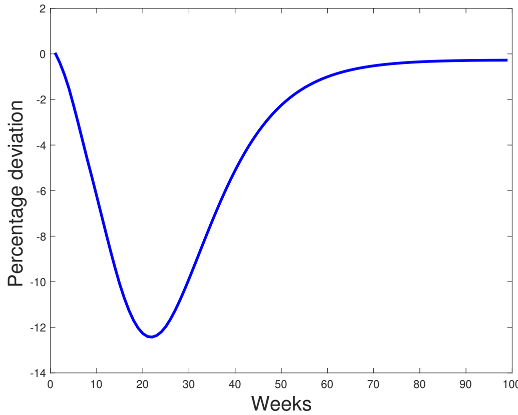
4. The transmission of monetary policy in a pandemic

In this section, we study how monetary policy transmits to the economy in our framework. First, we outline some mechanisms suggesting that monetary policy is weaker in a pandemic than in normal times. Second, we assess the relevance of these mechanisms by analyzing the response of output to changes in the real interest rate at different horizons and at different stages of the pandemic[7]. Third, we examine the effects on inflation and output of delaying lift-off by two quarters.

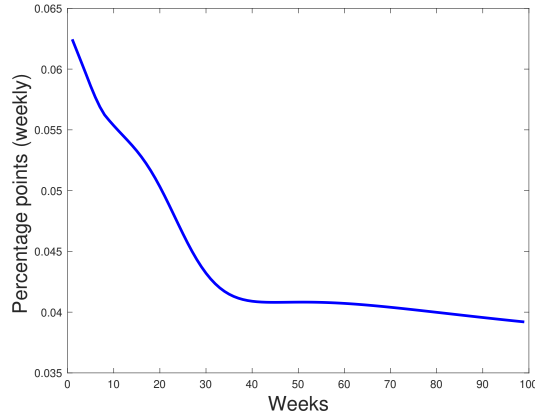
[6]CPI inflation actually decreased slightly during the pandemic. However, Cavallo (2020) shows that a sudden change in expenditure patterns introduced significant downward biases in the CPI. His evidence supports the view that lower demand and supply-side disturbances had roughly offsetting effects on inflation.

[7]In Appendix A, we conduct an alternative and complementary exercise. We assume that the effective lower bound on nominal interest rates does not bind and simulate the effects of persistent shocks to the monetary policy rule at different stages of the pandemic. The results from this experiment support our finding that monetary policy is weaker when the stock of infected individuals is large.

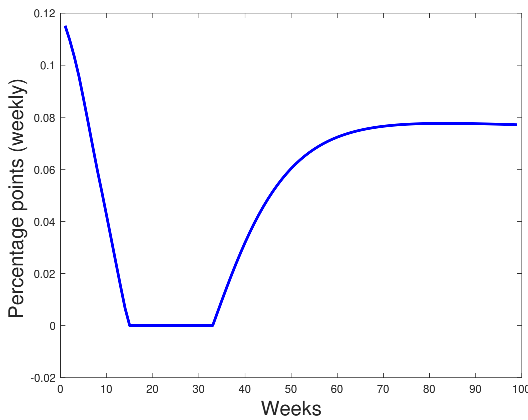
Figure 2. Economic Effects (weekly)



(a) Output



(b) Inflation



(c) Policy rate

4.1. What should we expect?

In our model, monetary policy transmits through the Euler equations of the different types of household members. While the Euler equations of infected and recovered individuals are standard, a new consumption-versus-health-risk motive appears in the Euler equation of susceptible individuals. Therefore, understanding how aggregate consumption reacts to changes in real interest rates during a pandemic requires: 1) tracking the fraction of individuals in each health state; and 2) understanding how the presence of the consumption-versus-health-risk motive shapes the response of susceptibles' consumption to real interest changes.

To tackle the second issue, we consider the Euler equation of susceptible individuals, equation 26. To lighten notation, we denote the consumption-versus-health-risk motive by Ω_t

$$\Omega_t = \beta \frac{\partial \tau_t}{\partial C_{s,t}} \left[V_{i,t+1} - V_{s,t+1} \right]. \tag{39}$$

Solving forward the Euler equation of susceptible individuals, we obtain

$$C_{s,t}^{-\sigma} + \Omega_t = \beta^n \left(C_{s,t+n}^{-\sigma} + \Omega_{t+n} \right) \prod_{j=0}^{n-1} RR_{t+j}, \tag{40}$$

where $RR_t = \frac{1+R_t^{mp}}{\Pi_{t+1}}$ is the real interest rate in period t.

We first study the time t effect of a decline in the real interest rate at time $t+h$ with $0 < h < n-1$ under the assumption that n is large enough such that, by time $t+n$, the pandemic has died out and economic outcomes are independent of real interest rate changes happening before $t+n$. The elasticity of time t consumption to a change in the real interest rate at time $t+h$ is given by

$$\frac{\partial C_{s,t}}{\partial RR_{t+h}} \frac{RR_{t+h}}{C_{s,t}} = -\frac{1}{\sigma} \frac{C_{s,t}^{-\sigma} + \Omega_t}{C_{s,t}^{-\sigma}} + \frac{1}{\sigma} \frac{\partial \Omega_t}{\partial RR_{t+h}} \frac{RR_{t+h}}{C_{s,t}^{-\sigma}} \tag{41}$$

In normal times, $\Omega_t = 0$ for all t so the elasticity is simply equal to $-1/\sigma$, regardless of the horizon of the shock. In a pandemic, the elasticity depends both on the value of Ω_t at the time of the shock, as captured by the first term on the right hand side of equation 41, and its responsiveness to interest rate changes, as captured by the second term on the right hand side of equation 41.

We start by considering the first term on the right hand side of equation 41. We note that $\Omega_t < 0$ since increasing one's consumption leads to a greater probability of being exposed to the virus, that is $\partial \tau_t / \partial C_{s,t} > 0$, and individuals would rather remain susceptible than being infected, that is $V_{i,t+1} - V_{s,t+1} < 0$. Thus, $\frac{C_{s,t}^{-\sigma} + \Omega_t}{C_{s,t}^{-\sigma}} < 1$ and, hence, we have that the first term in equation 41 is larger (smaller in absolute value) than $-1/\sigma$. In equation 40, a decline in the real interest rate results in a decrease in the term on the right hand side of the equation. In order to restore the equality, consumption $C_{s,t}$ needs to increase but, since utility is concave in consumption, the required increase is smaller the more negative Ω_t is. In turn, the higher the probability of being infected through consumption activities, the more negative Ω_t is and, hence, the smaller the expansion in consumption. Intuitively, individuals are much less willing to take advantage of intertemporal substitution opportunities when doing so involves a non-negligible risk of becoming sick. Thus, according to this channel, we expect: *(i)* the effects of monetary policy on consumption to be smaller during a pandemic than in normal times; and *(ii)* the effects of monetary policy to be the weakest at the peak of the pandemic, when the probability of getting infected is the highest.

Next, we assess how the response of Ω_t to the shock contributes to shaping the interest rate elasticity of consumption for susceptibles by analyzing the second term in equation 41. We have that

$$\frac{\partial \Omega_t}{\partial RR_{t+h}} = \beta \pi_{s1} I_t \left[\frac{\partial C_{i,t}}{\partial RR_{t+h}} \left[V_{i,t+1} - V_{s,t+1} \right] + C_{i,t} \frac{\partial \left[V_{i,t+1} - V_{s,t+1} \right]}{\partial RR_{t+h}} \right] \tag{42}$$

where I_t is predetermined within the period. The response of Ω_t to a change in the real interest rate depends on both the responses of $C_{i,t}$ and of $(V_{i,t+1} - V_{s,t+1})$. From the Euler equation of infected individuals, equation 27, we know that $\partial C_{i,t} / \partial RR_{t+h}$ is negative. $\partial \left(V_{i,t+1} - V_{s,t+1} \right) / \partial RR_{t+h}$ is also generally negative, as susceptible individuals benefit less (more) from a monetary policy easing (tightening) than infected individuals (because of a smaller increase in consumption and hours worked and a rise in the probability of infection). The sign of $\partial\Omega_t/\partial RR_{t+h}$ is therefore ambiguous. On the one hand, through an increase in $C_{i,t}$, a monetary easing triggers a rise in the probability of infection. On the other hand, through $V_{i,t+1} - V_{s,t+1}$, it leads to a decrease in the utility loss of infection. If the first effect dominates, susceptible individuals are incentivized to consume less, which further blunts the positive effects of the interest rate shock. If the second effect dominates, the reverse happens. In general, we find in our simulations that the impact response of Ω_t does not contribute meaningfully to the initial response of consumption to the shock. That is, the impact response of consumption is best characterized by ignoring the second term in equation 41.

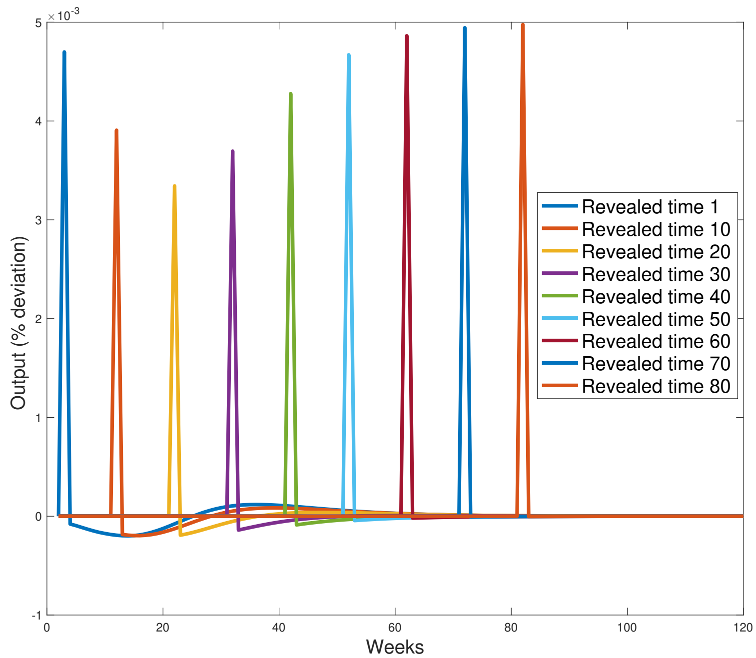
While we have so far focused on the effects of a real interest rate change in the period agents learn about this change, monetary policy influences economic activity beyond this initial period through its effect on epidemic dynamics. Notably, although movements in Ω_t are inconsequential for the response of consumption *on impact*, this is no longer the case in subsequent periods once infections I_t start responding to the shock. Consider for example the effects of a one-time decline in RR_t announced in period t. Initially, the easing of monetary policy provides a boost to economic activity. However, since the increase in economic activity necessarily requires an increase in social interactions, this inevitably leads to a rise in infections. In subsequent periods, once policy accommodation is removed, the economy is left with a larger stock of infected individuals, which depresses demand through the consumption-versus- health-risk motive: given that the perceived risk of infection has risen, susceptible individuals cut back on consumption purchases. Thus, because of the feedback between economic activity and infection dynamics, the monetary authority faces a dynamic trade-off. Any attempt to support aggregate demand in the present may result in lower aggregate demand tomorrow.

4.2. Monetary policy experiments

To illustrate the relevance of the mechanisms described above, we conduct several experiments. We consider the effects of one-time anticipated changes in the real interest rate announced in different periods t and with different horizons j. The real interest rate is held fixed at its steady-state value in all other periods. The dynamics of output and epidemiological variables in this economy with a real interest rate peg are qualitatively similar to those in the baseline economy of Section 3. In all our experiments, we consider the response of output. However, our results would be very similar if we considered aggregate consumption instead.

In our first experiment, we set $t = 1, ..., 80$ and $j = 0$ – that is, we examine the output effects of an *unanticipated* one basis point drop in the weekly real interest rate at any time between week 1 and week 80 of the pandemic. The left blue line in Figure 3 shows the response of output to an *unanticipated* shock revealed in week 1. The left orange line reports the response of output to an *unanticipated* shock revealed in week 10 of the simulation. The yellow line shows the response to a shock revealed in week 20, the purple line to a shock revealed in week 30, the green line to a shock revealed in week 40, the light blue line to a shock revealed in week 50, the red line to a shock revealed in week 60, the right blue line to a shock revealed in week 70, and the right orange line to a shock revealed in week 80.

Figure 3. IRFs to unanticipated changes in the real interest rate at different dates (week 1 to week 80)



Note: The left dark blue line shows the response of output to an unanticipated real rate shock revealed in week 1. The left orange line shows the response to a shock revealed in week 10. The yellow line shows the response to a shock revealed in week 20. The purple line shows the response to a shock revealed in week 30. The green line shows the response to a shock revealed in week 40. The light blue line shows the response to a shock revealed in week 50. The red line shows the response to a shock revealed in week 60. The right blue line shows the response to a shock revealed in week 70. The right orange line shows the response to a shock revealed in week 80.

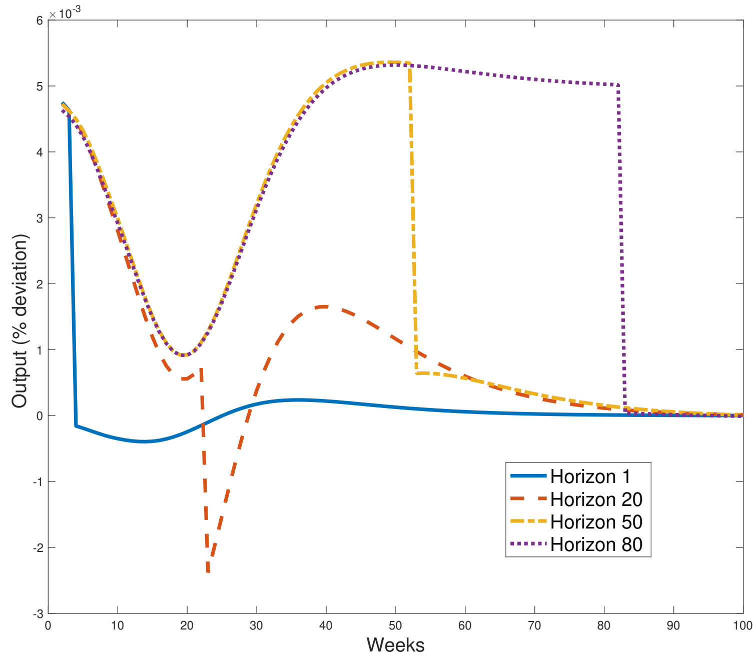
As shown in Figure 3, the effects of the real interest change on output are the smallest at the peak of the pandemic, around week 20. The effects are also smaller throughout the course of the pandemic than in normal times, thereby confirming the relevance of the consumption-versus-health-risk motive[8]. The negative effects on output are persistent even after policy accommodation is removed since the initial increase in output leads to new infections, which, in turn, depress output through the mechanisms described in Section 4.1.

In our second experiment, we set $t = 1$ and let the horizon j vary between 0 and 80 – that is, we examine the effect on output of a one basis point drop in the weekly real interest rate *announced* at time 1 and with a horizon comprised between 0 and 80 weeks. In Figure 4, we report in solid blue the response of output to an anticipated real rate shock in period 1. The dashed orange line shows the response of output to an anticipated real rate shock in period 20, while the two-dashed yellow line shows the response of output to an anticipated real rate shock in period 50 and the

[8]In a standard New Keynesian model, the output response would be equal to $5 * 10^{-3}$ at the time of shock and zero in all other periods.

dotted purple line to an anticipated real rate shock in period 80. Since a horizon of 0 corresponds to an unanticipated shock, the solid blue line in Figure 4 is the same as the first solid blue line in Figure 3.

Figure 4. IRFs to anticipated changes in the real interest rate. Anticipated at date 1, horizon 1, 20, 50, 80.

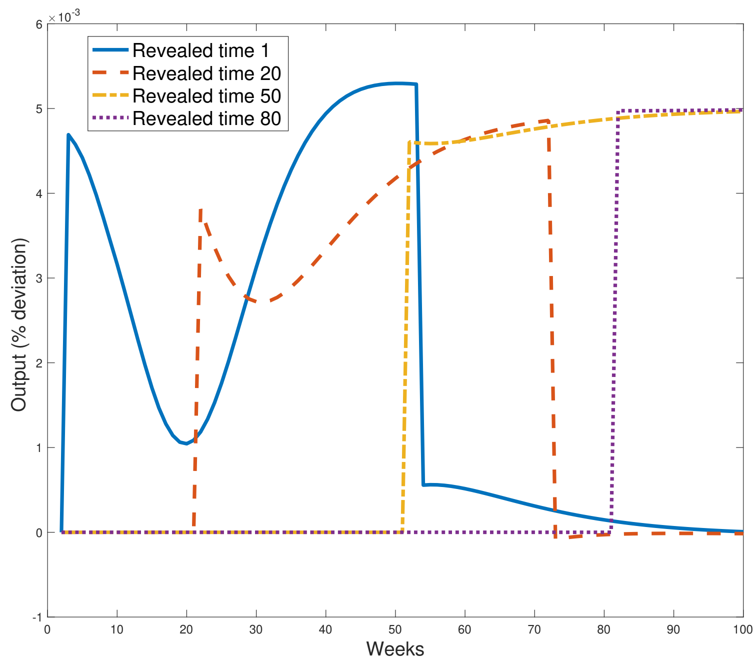


Note: The solid blue line shows the response of output at time 1 to an anticipated real rate shock in period 1. The dashed orange line shows the response of output at time 1 to an anticipated real rate shock in period 20. The two-dashed yellow line shows the response of output at time 1 to an anticipated real rate shock in period 50. The dotted purple line shows the response of output at time 1 to an anticipated real rate shock in period 80.

Let us focus our discussion on the response of output to an anticipated decline in the real interest rate at an horizon of 20 weeks. The response of output is initially quite strong but declines abruptly as the epidemic progresses. As the probability of becoming infected while consuming increases, households become less willing to take advantage of intertemporal substitution opportunities. Policy accommodation is removed in period 21, which brings the response of output to negative territory. Indeed, the prolonged boost to economic activity between periods 1 and 20 increases the number of new infections, leaving households with a greater desire to postpone consumption compared to a case without monetary policy stimulus. After period 30, the output response bounces back above zero. Since infections have been brought forward in time, the economy is left with less susceptible individuals and the spread of the virus slows down, thereby accelerating the recovery from the pandemic. A similar pattern can be observed for the responses of output to anticipated decreases in the real interest rate at longer horizons, with the noticeable exception that the drop in output at the peak of the pandemic is smaller, reflecting the fact that monetary policy accommodation is removed later in those simulations, once the pandemic is already under control[9].

In the third experiment, we set $j = 50$ and let time t vary between 1 and 80 – that is, we examine the output effects of a one basis point drop in the weekly real interest rate *announced* at any time between week 1 and week 80 and with a fixed horizon of 50 weeks. In Figure 5, the solid blue line shows the response of output to an anticipated real rate shock announced in period 1, the dashed orange line shows the response of output to an anticipated shock announced in period 20, the two-dashed yellow line shows the response to an anticipated shock announced in period 50, and the dotted purple line shows the response of output to an anticipated shock announced in period 80.

Figure 5. IRFs to anticipated changes in the real interest rate. Horizon 50, revealed at time 1, 20, 50, 80.



Note: The solid blue line shows the response of output at time 1 to an anticipated monetary policy shock announced in period 1 and with a fixed horizon of 50 weeks. The dashed orange line shows the response of output at time 1 to an anticipated monetary policy shock announced in period 20 and with a fixed horizon of 50 weeks. The two-dashed yellow line shows the response of output at time 1 to an anticipated monetary policy shock announced in period 50 and with a fixed horizon of 50 weeks. The dotted purple line shows the response of output at time 1 to an anticipated monetary policy shock announced in period 80 and with a fixed horizon of 50 weeks.

The response of output is U-shaped and qualitatively similar regardless of the timing of the announcement. In the downward-sloping part of the U, the number of new infections brought about by the shock builds up before reaching a peak. In the upward-sloping part of the U, new infections gradually decline. However, the quantitative effects of these anticipated shocks are state-dependent.

[9] For comparison, in a standard New Keynesian model, such an anticipated decline in the real interest rate at horizon j would lead to an output response equal to $5 * 10^{-5}$ from periods 1 to j and zero afterwards.

If the announcement takes place early in the pandemic, when a large fraction of individuals are susceptible to the virus, the build-up in infections is large and the U-shaped response of output is very pronounced. See, for example, the blue solid line versus the dashed orange line in Figure 5. If the announcement takes place later during the pandemic, when a significant fraction of the population has already been infected and recovered, the build-up in infections is much smaller and the U-shaped response of output is less pronounced. See, for example, the dashed orange line versus the two-dashed yellow line in Figure 5.

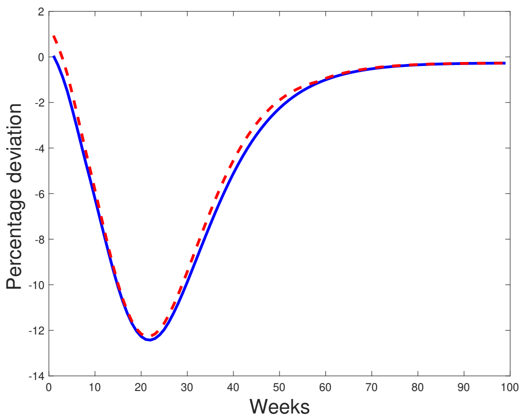
From these experiments, we conclude that monetary policy is likely to be ineffective at the height of the pandemic. It could, however, help sustain the recovery in economic activity once the virus starts dissipating.

4.3. A delayed lift-off

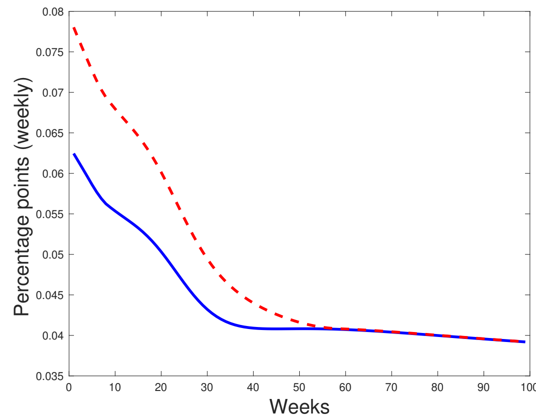
To build intuition, we have thus far assumed that there is no feedback from changes in output and inflation back onto real interest rates. However, in practice, when the policy rate is constrained by the effective lower bound, as is the case in our baseline economy, forward guidance about lower nominal interest rates reduces real interest rates both at the time of the announcement and before the announcement through endogenous movements in inflation. In this section, we examine the effects of such forward guidance policies. In our baseline economy, described in Section 3, the federal funds rate stayed at the effective lower bound from weeks 14 to 34. We now assume that the central bank delays lift-off by another 26 weeks, or two quarters.

Figure 6 shows the economic effects of a pandemic under the baseline policy rule subject to the effective lower bound in blue, and under the delayed lift-off policy in red. The delayed lift-off policy leads to a marked increase in inflation. In order to serve the higher demand brought about by the change in policy, firms attempt to increase hours, which puts upward pressure on wages and, ultimately, prices as susceptible individuals are still reluctant to participate in the labor market. In turn, with the federal funds rate at the effective lower bound, the rise in inflation leads to a large decline in the real interest rate, which further stimulates economic activity. Initially, the delayed lift-off policy cushions the decline in economic activity, although the effects are small. However, as the epidemic progresses, the effects of forward guidance become less stimulative. In particular, forward guidance is not effective at softening the magnitude of the peak decline in output. Indeed, the trough in output is reached at the height of the pandemic, when the interest-sensitivity of consumption is the lowest. Furthermore, as shown in Figure 7, the higher initial path of economic activity under the delayed lift-off policy leads to an increase in infections, which in turn reinforces households' incentives to postpone consumption until the risk of infection wanes. Once the situation on the epidemiological front starts improving, around week 30, the economy recovers at a faster pace under the delayed lift-off policy. Indeed, as the effects of the virus dissipate, the behavior of households returns to normalcy and forward guidance regains its effectiveness. Such a policy is, however, ineffective at sustaining economic activity at the height of the pandemic.

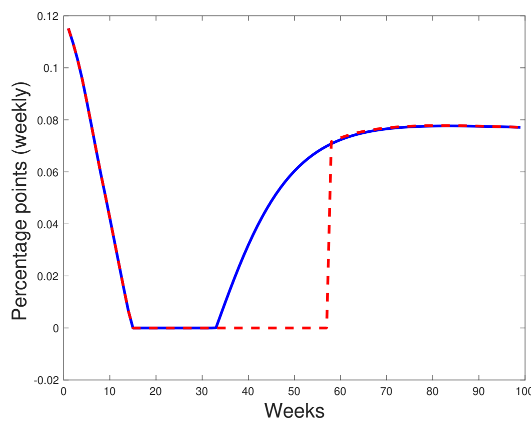
Figure 6. Economic Effects (weekly)



(a) Output



(b) Inflation



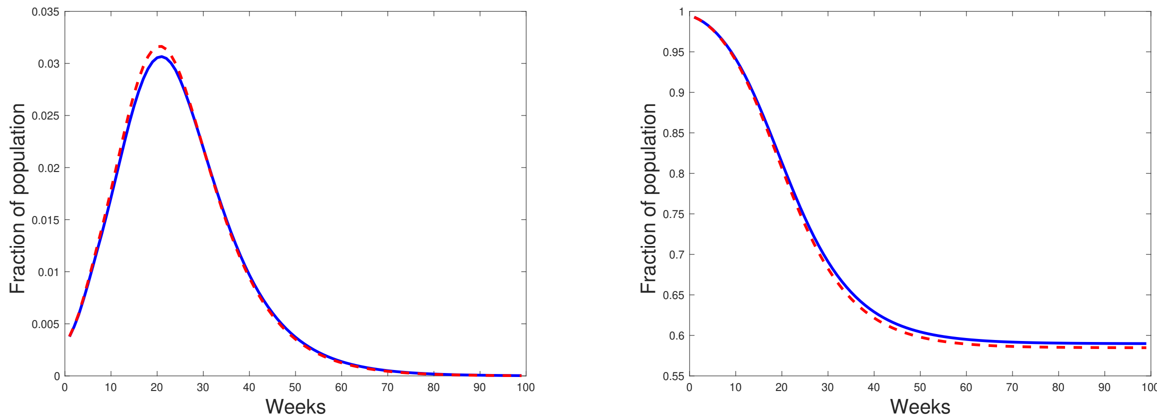
(c) Policy rate

Note: The blue line represents the outcomes in the baseline economy. The red dashed line represents the outcomes in the economy with a delayed lift-off policy.

5. What should monetary policy do in a pandemic?

While we have so far shown that the effectiveness of monetary policy during a pandemic can be weaker, we have not analyzed how monetary policy should *optimally* be conducted in this context. Notably, a benevolent planner would likely weigh the limited gains in the stabilization of real activity against the human costs of additional infections when setting a path for the nominal interest rate. We turn to this issue in this section. In order to clarify which inefficiencies arise in the decentralized equilibrium, and how monetary policy can attempt to correct for them, we first compare the decentralized equilibrium with the allocation that a planner would achieve. The planner seeks

Figure 7. Epidemiological Effects (weekly)



(a) Infected (b) Susceptible

Note: The blue line represents the outcomes in the baseline economy. The red dashed line represents the outcomes in the economy with a delayed lift-off policy.

to maximize the intertemporal utility of households subject to the population dynamics equations and the economy-wide resource constraint. Formally:

$$V(S_t, I_t, R_t) = \max_{C_{s,t}, C_{i,t}, C_{r,t}, N_{s,t}, N_{i,t}, N_{r,t}} \{S_t u(C_{s,t}, N_{s,t}) + I_t u(C_{i,t}, N_{i,t}) + R_t u(C_{r,t}, N_{r,t}) + \beta V(S_{t+1}, I_{t+1}, R_{t+1})\} \quad (43)$$

subject to

$$S_t C_{s,t} + I_t C_{i,t} + R_t C_{r,t} = A(S_t \phi_s N_{s,t} + I_t \phi_i N_{i,t} + R_t \phi_r N_{r,t}) \quad (44)$$

$$S_{t+1} = S_t - \pi_{s1} S_t C_{s,t} I_t C_{i,t} - \pi_{s2} S_t N_{s,t} I_t N_{i,t} - \pi_{s3} S_t I_t \quad (45)$$

$$I_{t+1} = (1 - \pi_r - \pi_d) I_t + \pi_{s1} S_t C_{s,t} I_t C_{i,t} + \pi_{s2} S_t N_{s,t} I_t N_{i,t} + \pi_{s3} S_t I_t \quad (46)$$

$$R_{t+1} = R_t + \pi_r I_t \quad (47)$$

The first-order conditions are:

$$u_c(C_{s,t}, N_{s,t}) + \beta \pi_{s1} I_t C_{i,t} (V_{i,t+1} - V_{s,t+1}) = \lambda_t \quad (48)$$

$$u_c(C_{i,t}, N_{i,t}) + \beta \pi_{s1} S_t C_{s,t} (V_{i,t+1} - V_{s,t+1}) = \lambda_t \quad (49)$$

$$u_c(C_{r,t}, N_{r,t}) = \lambda_t \quad (50)$$

$$u_n(C_{s,t}, N_{s,t}) + \beta \pi_{s2} I_t N_{i,t} (V_{i,t+1} - V_{s,t+1}) = -\lambda_t A \phi_s$$

$$u_n(C_{i,t}, N_{i,t}) + \beta \pi_{s2} S_t N_{s,t} (V_{i,t+1} - V_{s,t+1}) = -\lambda_t A \phi_i \quad (51)$$

$$u_n(C_{r,t}, R_{r,t}) = -\lambda_t A \phi_r \quad (52)$$

And the envelope conditions are:

$$\begin{aligned} V_{s,t} &= u(C_{s,t}, N_{s,t}) + \lambda_t (A\phi_s N_{s,t} - C_{s,t}) + (1-\tau_t)\beta V_{s,t+1} + \tau\beta V_{i,t+1} && (53)\\ V_{i,t} &= u(C_{i,t}, N_{i,t}) + \lambda_t (A\phi_i N_{i,t} - C_{i,t}) \\ &\quad + (1-\pi_r-\pi_d)\beta V_{i,t+1} + \pi_r\beta V_{r,t+1} + \beta\tau_t\frac{S_t}{I_t}(V_{i,t+1} - V_{s,t+1}) && (54)\\ V_{r,t} &= u(C_{r,t}, N_{r,t}) + \lambda_t (A\phi_r N_{r,t} - C_{r,t}) + \beta V_{r,t+1} && (55) \end{aligned}$$

where λ_t is the Lagrange multiplier associated with the budget constraint. We highlight in red and blue the differences with the decentralized equilibrium. Three types of distortions arise in the decentralized equilibrium: *(i)* for a given level of output, the presence of price adjustment costs reduces the amount of resources available for consumption, as can be seen by comparing equations 36 and 44 ; *(ii)* monopolistic competition drives a wedge between the marginal rate of substitution between consumption and hours worked and the marginal product of labor (terms in blue); *(iii)* households do not internalize the effects of the consumption and labor supply decisions of infected individuals on the dynamics of the epidemic (terms in red).

While the first two distortions are standard in New Keynesian models and imply that the monetary authority should focus on stabilizing inflation, the third distortion is specific to the context of a pandemic. Infected individuals consume and work too much and, in doing so, contribute to the spread of the virus. This has two implications for monetary policy. First, since monetary policy affects the consumption of all individuals in a similar way, it is not particularly effective at addressing this infection externality. The same shortcoming is shared by other policies that affect individuals equally despite their health status. More appropriate policies would target infected individuals directly. Second, assuming that such targeted policies are not available and that the decentralized equilibrium remains inefficient, the overall level of economic activity in the decentralized equilibrium is too high. That is, the planner would be willing to engineer a decline in consumption and hours worked for *all* individuals in order to limit the spread of the virus within the population (see, for example, Eichenbaum, Rebelo and Trabandt, 2021, Jones, Philippon and Venkateswaran, 2020, and Farboodi, Jarosch and Shimer, 2021, among others).

With output too high and inflation above target in our baseline economy (see upper right panel in Figure 2), it seems natural to think that looser monetary policy, which is required to cushion the decline in economic activity, will not be welfare-improving. We now provide evidence for this conjecture by comparing the levels of welfare attained under three different policies: *(i)* the baseline rule; *(ii)* the delayed lift-off policy considered in section 4.3; and *(iii)* the constant real interest rate policy around which we conducted our monetary policy experiments in section 4.2. The real interest rate path is shallower under the delayed lift-off policy than in the baseline, while it is more restrictive in the constant real interest case. We define welfare as the lifetime utility of households evaluated at the start of the simulation (time 0) and measure the welfare costs of adopting another policy (policy A for alternative) than the baseline rule (policy B for baseline), ω, as the fraction of the consumption process under the baseline policy that households would have to give up to be as well-off under the baseline policy as under the alternative policy. ω is implicitly defined as:

$$\sum_{t=0}^{\infty} S_t^B u\left(C_{s,t}^B\left(1-\omega\right), N_{s,t}^B\right) + I_t^B u\left(C_{i,t}^B\left(1-\omega\right), N_{i,t}^B\right) + R_t^B u\left(C_{r,t}^B\left(1-\omega\right), N_{r,t}^B\right)$$
$$= \sum_{t=0}^{\infty} S_t^A u\left(C_{s,t}^A, N_{s,t}^A\right) + I_t^A u\left(C_{i,t}^A, N_{i,t}^A\right) + R_t^A u\left(C_{r,t}^A, N_{r,t}^A\right),$$

A positive value for ω indicates a welfare cost while a negative value indicates a welfare gain. The results are reported in Table 1. The baseline rule is preferred over the delayed lift-off policy while the constant real interest rate policy is preferred over the baseline rule. Thus, welfare is higher under the tighter policy, thereby confirming our conjecture that loose monetary policy is not desirable from a welfare standpoint.

Table 1: Welfare comparison

	Delayed lift-off	Constant real interest rate
ω	0.016%	-0.021%

Interestingly, these findings are consistent with the views expressed by U.S. policymakers during the pandemic. For example, in March 2020, Bullard (2020) noted that the goal of macroeconomic policy in a pandemic is not to stimulate the economy but rather to strive to "keep everybody whole". Although the U.S. economy was experiencing its most severe downturn since the Great Depression, the word "stimulus" remained conspicuously absent from speeches made by FOMC members throughout the first stage of the pandemic. Instead, policymakers insisted on the necessity for monetary policy to "provide a measure of relief and stability" and "support the economic recovery when it comes" (Powell, 2020). In these speeches, policymakers refer, among other things, to the deployment of facilities aimed at stabilizing financial markets and avoiding the disruption of the flow of credit to households and businesses. Given its simplicity, our model cannot speak to these issues. However, our results certainly support the idea that the stance of monetary policy should not be stimulative in the midst of a pandemic.

6. Robustness

More than a year after the start of the COVID-19 pandemic, there is still a great deal of uncertainty about the parameters governing the evolution of the virus. In this section, we study the sensitivity of our results to variations in the basic reproduction number, $\mathcal{R}_0$, the per-period probability of dying when infected or mortality rate, π_d, and the flow value of being alive, $\bar{u}$. We also examine how our results change in the presence of non-pharmaceutical interventions (NPIs). All robustness exercises are conducted feeding the model economy with the same sequence of shocks as in the baseline except for the case of NPIs. We focus our analysis on the following statistics: the peak infection rate, the timing of the peak, the overall size of the pandemic measured by the percentage of susceptible individuals at the end of it, the maximum drop in output, and a measure of the effectiveness of monetary policy. This last statistic is computed as the increase in output generated by an unanticipated one basis point drop in the weekly real interest rate at the peak of the pandemic (the first experiment in Section 4.2) divided by the increase in response to the same shock in the absence of a pandemic. We divide Table 2 in four sections, one for each variation we are analyzing. The first row for each section in Table 2 corresponds to the baseline described in Section 3.2.

Table 2: Robustness

	Infection rate	Timing	Susceptibles	Output	MP effectiveness
Basic reproductive number					
$\mathcal{R}_0 = 2$	3.07	22	59.0	-12.4	68%
$\mathcal{R}_0 = 1.5$	0.32	4	97	-1.94	94%
$\mathcal{R}_0 = 2.5$	10.4	15	33.7	-20.4	52%
Mortality rate					
$\pi_d = 0.008 * 7/15$	3.07	22	59.0	-12.4	68%
$\pi_d = 0.004 * 7/15$	3.56	22	55.9	-7.6	78%
$\pi_d = 0.016 * 7/15$	2.49	22	62.8	-18.6	54%
Flow value of being alive					
$\bar{u} = 5.4$	3.07	22	59.0	-12.4	68%
$\bar{u} = 2.9$	3.74	23	54.8	-6.05	82%
$\bar{u} = 4.3$	3.33	22	57.4	-10.0	72%
Better health policies					
Baseline	3.07	22	59.0	-12.4	68%
25% better	1.62	22	71.0	-6.6	80%
50% better	0.77	7	91.2	-4.2	86%

The first section in Table 2 reports the results for alternative basic reproduction numbers, $\mathcal{R}_0$. In our baseline, $\mathcal{R}_0 = 2$ and we explore two alternative values: $\mathcal{R}_0 = 1.5$ and $\mathcal{R}_0 = 2.5$. Our choice of $\mathcal{R}_0 = 1.5$ is informed by the median estimate among U.S. counties in Sy, White and Nichols (2021), $\mathcal{R}_0 = 1.66$, and by the estimated basic reproduction number for other pathogens such as, for example, the 2009 influenza strain in Biggerstaff et al. (2014), $\mathcal{R}_0 = 1.46$. In this case, the pandemic is much smaller than in the baseline with only 3 percent of the population getting infected by the end of it. The peak infection rate is just 0.32 percent and output drops by less than 2 percent. Given the mild epidemiological outcomes, an unanticipated monetary policy shock at the peak of the pandemic generates an expansion in output close to that in normal times.

Bar-On et al. (2020) provide a range of estimates for $\mathcal{R}_0$ between 2 and 6, while Chudik, Pesaran and Rebucci (2021) suggest $\mathcal{R}_0$ is in the range of 2.4 to 3.9. As shown in Table 2, for a basic reproduction number of 2.5, the pandemic is much larger: the peak infection rate is 10.4 percent and the fraction of susceptible individuals at the end of the pandemic is about 34 percent. In this case, the drop in output is slightly above 20 percent. As shown in the last column in Table 2, an unanticipated monetary policy shock at the peak of the pandemic has smaller expansionary effects in real economic activity than in the baseline. This confirms that the effectiveness of monetary policy is, in part, related to the size of the pandemic: when the probability of infection rises, individuals are more reluctant to take advantage of intertemporal substitution opportunities and monetary policy becomes less effective.

In our baseline, we assume an infection fatality rate of 0.8 percent, which implies a weekly mortality rate, π_d, of 0.37 percent. We consider two alternatives: first, an infection fatality rate of 0.4 percent, which implies a weekly mortality rate of 0.19 percent, and an infection fatality rate of 1.6 percent, which implies a weekly mortality rate of 0.75 percent. As shown in the second panel in Table 2, variations in the mortality rate have smaller effects on epidemiological outcomes than variations in the basic reproduction number. However, the economic effects implied by changes in the mortality rate are sizable. For example, if the mortality rate is about half that in the baseline, the drop in output is about 40 percent smaller. Similarly, when the mortality rate doubles, the drop in output at the peak of the pandemic is about 50 percent larger. Indeed, when the probability of death increases, individuals have more to lose from becoming infected and they cut back more drastically on consumption and hours worked. They also become more reluctant to adjust consumption in response to real interest changes: as shown in the last column in Table 2, the effectiveness of monetary policy is a decreasing function of the infection fatality rate.

The third panel in Table 2 explores the sensitivity of our results to the valuation of a statistical life (VSL). The VSL in our baseline does not adjust by life expectancy at the age of death. Robinson, Sullivan and Shogren (2021) use three approaches to adjust for age: an invariant population-average VSL, a constant value per statistical life-year, and a VSL that follows an inverse-U pattern peaking around middle age. When applying these approaches to the U.S. age distribution of COVID-19 deaths, they obtain average VSL estimates of $10.6 million, $4.5 million, and $8.5 million respectively. In our framework, those VSL estimates imply the following values for the flow value of life: 5.1, 2.9, and 4.3, respectively. We report in Table 2 the results for $\bar{u} = 2.9$ and $\bar{u} = 4.3$. As shown in Table 2, variations in the VSL have limited effects on epidemiological outcomes but significant effects on economic outcomes. A 25 percent reduction in VSL implies a drop in output that is 20 percent smaller as shown in the third row of the third panel in Table 2. Similarly, as shown in the second row of the panel, a VSL 60 percent smaller than in the baseline implies a maximum decline in output that is half the size of that in the baseline. The last column shows that monetary policy regains its effectiveness as the VSL decreases. The intuition for this result is similar to the one outlined above in the case of the mortality rate: with a smaller VSL, individuals are less concerned about the risk of infection and become more willing to engage in economic activities.

In the last panel in Table 2, we explore non-pharmaceutical interventions (NPIs) in the form of mask wearing, changes in consumption behavior (ordering take-out instead of eating at restaurants), or opting for teleworking more often, which are not captured in our baseline calibration. These improvements in the infection technology can be modeled through decreases in π_{s1} and π_{s2}. We refer to them as "better health policies", although they encompass not only government interventions but also changes in individual behavior. We explore two cases for "better health policies": *(i)* π_{s1}

and π_{s2} decline by 25 percent starting in week 5 and until the end of the simulation and *(ii)* π_{s1} and π_{s2} decline by 50 percent starting in week 5 and until the end of the simulation. Better health policies translate into better epidemiological and economic outcomes than in the baseline. Given the milder epidemiological outcomes, monetary policy is more effective under both NPIs than in the baseline.

7. Conclusion

In response to the COVID-19 shock, central banks around the world acted swiftly and forcefully by cutting short-term interest rates, extending forward guidance and asset purchases, and providing liquidity and credit support (English, Forbes and Ubide, 2021). In this paper, we develop a framework where economic decisions and virus dynamics are interlinked and we analyze the role played during a pandemic by two monetary policy tools: conventional interest rate policy and forward guidance.

Our first main result pertains to the effectiveness of monetary policy. We find that monetary policy is generally less effective in a pandemic than in normal times. In the model, the transition probability from being healthy (susceptible) to sick (infected) depends on households' consumption and labor supply decisions. In a pandemic, individuals have to balance the benefits of taking advantage of intertemporal substitution opportunities with the risk of becoming sick. As a result, decreases in real interest rates are less effective at propping up economic activity than in normal times. The strength of this channel is strongly state-dependent: individuals are the most reluctant to engage in intertemporal substitution when the stock of infected individuals — and, thus, the probability of infection — is the largest.

Our second main result pertains to the desirability of policy interventions aimed at stimulating economic activity during a pandemic. We find that monetary policy is poorly equipped to address the main inefficiency arising in the decentralized equilibrium, namely the fact that infected individuals do not internalize the effects of their actions on the dynamics of the epidemic. In the absence of tools targeted directly at infected individuals, the level of economic activity in the decentralized equilibrium is too high, which implies that an easing of monetary policy conditions is not welfare improving.

Our paper is a first step to understanding whether monetary policy transmits, and should be conducted, differently in a pandemic than in normal times. Our model is simple enough to allow us to trace the inner workings of the transmission of monetary policy, but this comes at the expense of abstracting from any source of heterogeneity across individuals besides their health status. Interesting avenues for future research include extending the analysis, at the risk of making it less transparent, to introduce features that have loomed large in the health crisis and its economic fallout, such as wealth inequality and sectoral and occupational heterogeneity, as in Kaplan, Moll and Violante (2020), or heterogeneity in the exposure to the virus by age, as in Hur (2020).

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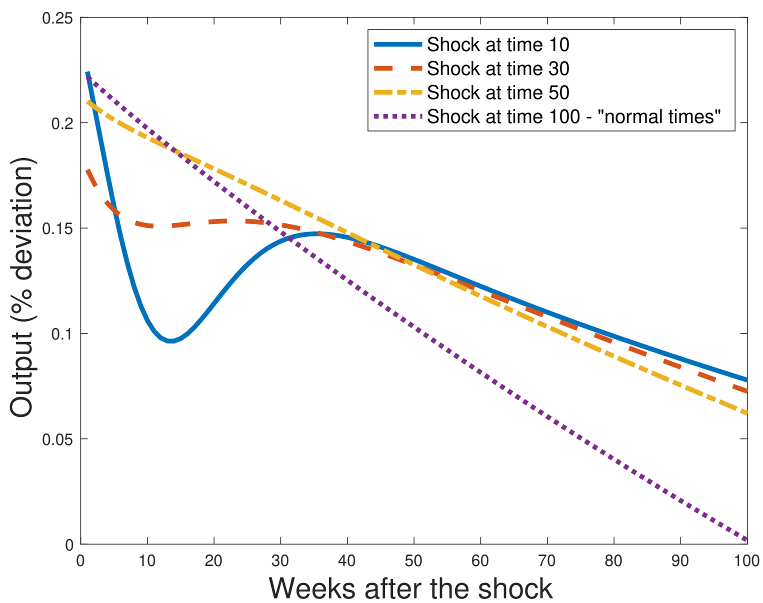
Appendix A. Additional monetary policy experiment

In this appendix, we propose an alternative experiment to illustrate the state-dependent nature of the effects of monetary policy in our framework. In a first stage, we simulate a pandemic of moderate size, as in section 3.2, but we now assume that the monetary authority is not subject to the effective lower bound on nominal interest rates. In a second stage, we compute impulse response functions to shocks to the monetary policy rule at different points in the pandemic (weeks 10, 30, 50, 100). The initial impulse (before the policy rate adjusts endogenously with movements in output and inflation) is a one basis point shock to the weekly interest rate with a persistence of 0.99, also at a weekly frequency. Figure 8 reports the results. We see that the effects of monetary policy are significantly weaker at the height of the pandemic (weeks 10 and 30) than in normal times (week 100).

Figure 8. IRFs to Monetary Policy Shocks at time 10, 30, 50, 100.



Note: The solid blue line shows the response of output to a monetary policy shock at time 10. The dashed orange line shows the response of output to a monetary policy shock at time 30. The two-dashed yellow line shows the response of output to a monetary policy shock at time 50. The dotted purple line shows the response of output to a monetary policy shock at time 100.