The effects of monetary policy through housing and mortgage choices on aggregate demand

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Abstract

Housing and mortgage choices are among the largest financial decisions households make and they substantially impact households' liquidity. This paper explores how monetary policy affects aggregate demand by influencing these portfolio choices. To quantify this channel, I build a heterogeneous-agent life-cycle model with long-term mortgages and endogenous house prices. I find that, although only a small fraction of households adjust their housing and mortgage holdings in response to an expansionary monetary policy shock, these households account for over 50 percent of the increase in aggregate demand. Mortgage refinancing explains approximately four-fifths of the contribution, whereas adjusted housing choices account for one-fifth—uncovering a new transmission channel. I also show that the different pass-through of the policy rate to short and long mortgage rates drives the difference in the house-price and aggregate demand response between economies with adjustable-rate as compared to fixed-rate mortgages.

Keywords: Monetary policy, household finance, housing, mortgages, life cycle

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1 Introduction

In this paper I build a quantitative heterogeneous-agent model to explore the relevance of the interactions between monetary policy and the housing market for aggregate demand. Two broad observations motivate my study.

First, in the U.S. over 40 percent of households have a mortgage and the outstanding mortgage debt surpassed USD 15.5 trillion in 2019, which corresponds to about 70 percent of GDP. Hence, changes in mortgage interest rates can substantially impact many households' finances. Moreover, the prevailing mortgage interest rate is an important input when households decide on what houses (if any) they can afford, which in turn affects house prices. With housing being the largest asset on most American households' balance sheets, this channel is potentially an important transmission mechanism of monetary policy into the real economy and aggregate demand, via the pass-through of the central bank's policy rate to mortgage interest rates. Indeed, since the Great Recession, there has been an increased focus on mortgage and housing markets among policy makers. Central banks in many countries are concerned with the extent to which monetary policy affects house prices and household debt, and ultimately how these effects impact consumption demand.

Second, we know that the liquidity positions of households are important for the transmission of monetary policy. Households that are liquidity constrained tend to have strong demand responses to changes in their cash flows, as emphasized in the heterogeneous agent New Keynesian literature (see Kaplan et al. (2018)). Importantly, both mortgage and housing choices tend to involve substantial cash flows and significantly alter households' liquidity. Hence, if liquidity-constrained households adjust these choices in response to changes in interest rates it can have real and direct implications for aggregate demand.

In my heterogeneous-agent life-cycle model I analyze these forces. I investigate the role that choices in the housing and mortgage market play for the aggregate demand response of monetary policy.[1] By constructing a model that captures the frictions in these markets, I study how different households' mortgage and housing choices influence their spending, when interest rates change. Furthermore, by including endogenous house prices, I quantify

[1]My focus is on changes in consumption demand, and I use the terms aggregate demand, aggregate consumption, and aggregate spending, interchangeably.

the importance of house-price changes for these portfolio choices. To analyze the effects of monetary policy, I feed in an exogenous real interest rate path, which corresponds to an empirically estimated response from an expansionary monetary policy shock. I find that although only a small share of households make extensive-margin adjustments of their portfolio of housing and mortgages in response to the shock, this group accounts for approximately 50 percent of the increase in aggregate spending. Specifically, I document a new channel of monetary transmission, namely, households who update their housing choice. These households account for about 10 percent of the increase in aggregate consumption. Together with households who refinance their mortgage, they are the main contributors to the increase in demand. I also show that the aggregate consumption response is highly dependent on the pass-through of the policy rate to mortgage interest rates. The stronger the pass-through, the larger is the house-price response, which in turn amplifies the demand response. In fact, the different pass-through to short and long mortgage rates can fully explain the difference in the aggregate spending response in economies with primarily adjustable-rate as compared to fixed-rate mortgages. The different house-price responses in these two settings account for almost 50 percent of the difference in aggregate demand.

To explore these mechanisms it is important to model the mortgage and housing markets in sufficient detail. In the model, households choose how much to consume, whether to rent or own a house, their house size, mortgage financing in fixed-rate 30-year contracts, and savings in risk-free liquid bonds. Importantly, owned housing is illiquid and markets are incomplete as households cannot fully insure against idiosyncratic earnings risks. There are two features of the housing market that create the illiquid nature of housing equity. First, households pay transaction costs to buy or sell a house. Second, if a homeowner wants to access its housing equity by taking up a larger mortgage, it incurs refinancing costs. Additional features of the housing market include down-payment and payment-to-income requirements that have to be fulfilled when purchasing a home or refinancing a mortgage.

Since households cannot perfectly insure against earnings risks, there are households who are constrained due to poor earnings realizations. Furthermore, since housing wealth is illiquid, there are also some relatively wealthy households that are constrained in their spending. In particular, many young homeowners use large mortgages to finance their house purchase and save little as they expect higher earnings in the future. These homeowners are therefore relatively liquidity constrained and have high exposures to changes in interest rates. Notably, in this model, households may endogenously generate substantial changes in their cash flows in response to monetary policy. When the mortgage interest rate changes, some households find it optimal to adjust their mortgage and housing holdings, with large implications for their liquidity. Hence, unlike in standard models, where changes in cash flows from a monetary policy shock only occur over time in the form of changes in the return on savings and through general-equilibrium effects on earnings, in this model some households instantly realize sizeable changes in their cash flows.

The calibrated model matches salient life-cycle and cross-sectional features of the U.S. data, relating to housing, mortgage debt, and liquid savings. To then study how households respond to monetary policy shocks, I use shocks to the real interest rate that are empirically estimated. In the main analysis, I consider a -100 basis points (bp) shock to the nominal interest rate, which affects the economy through its impact on the real interest rates on bonds and mortgages.

Results on aggregate responses and portfolio choice

In response to the expansionary monetary policy shock, I find that house prices rise by 2.6 percent and aggregate consumption demand increases by 1.1 percent. Moreover, I find that households' discrete portfolio adjustments of whether to rent, buy, move, or stay in a house, and the use of mortgage refinancing, substantially impact the effect on aggregate demand. Specifically, if restricting households to make the same extensive-margin portfolio choices as they had done without the shock, the aggregate demand response is approximately 50 percent lower, even though this constraint only affects 7 percent of households.[2] Furthermore, I find that both the pass-through of the monetary policy shock to mortgage interest rates as well as the response in house prices are important for the response in aggregate consumption. The change in the mortgage rate and house prices triggers extensive-margin portfolio adjustments, and each price change accounts for roughly one third of the increase in aggregate demand.

[2] In this exercise, I force households to choose the same house size and the same discrete mortgage and tenure choice (rent, buy a house, refinance, move, or stay in a house) as if the shock had not occurred.

The decline in the mortgage interest rate causes almost all of the increase in house prices. Most households who buy a house finance the purchase with a mortgage. By purchasing a house, a household can immediately transform the negative income effect from the lower return on savings into a benefit of lower interest payments on debt. As a result, the demand for housing increases, and there is a rise in the equilibrium house price.

When mortgage interest rates decrease and house prices rise, many households would like to take up a larger mortgage and reoptimize their choice of housing. However, due to frictions and adjustment costs in these markets, only a small share of households find it worthwhile to make such discrete reallocations. Importantly, the liquidity-constrained homeowners are among those who benefit the most from adjusting, since by doing so they can access their illiquid housing wealth. With higher liquid savings they are able to improve their consumption smoothing by directly increasing spending.[3] Specifically, I find that homeowners who use cash-out refinancing in response to the expansionary monetary policy shock account for approximately 40 percent of the increase in aggregate demand, a channel emphasized in previous literature. However, liquidity-constrained homeowners have two viable options to access their illiquid housing wealth: sell the house and move to a new owner-occupied house or move to rental housing. Since the lower mortgage interest rate causes house prices to rise, it is a particularly good alternative to sell a house. Overall, households who adjust their housing choice due to the interest rate shock account for about 10 percent of the increase in aggregate demand. Hence, I document and quantify an additional channel that can explain a significant share of the increase in aggregate spending.

Mortgage interest rates and contracts

Given the strong link between mortgage interest rates and house prices, and in turn aggregate demand, I proceed by exploring mortgage rates further. Empirical findings suggest that the pass-through of temporary changes in the central bank's policy rate to long mortgage rates varies substantially over time (Berger et al., 2018; Del Negro and Otrok, 2007; Scharfstein and Sunderam, 2013; Wong, 2021). I investigate the importance

[3] In terms of welfare, different households are differently affected by monetary policy. Specifically, welfare effects of an expansionary monetary policy shock are positively correlated with LTV and the direct increase in consumption, and negatively correlated with age and liquid savings-to-earnings.

of this pass-through rate for monetary policy transmission, and find that it is a main determinant of both house-price and aggregate demand responses. The findings also indicate that the difference in the pass-through rate to long mortgage rates as compared to short rates, can fully account for the difference in the responses in house prices and consumption in economies with adjustable-rate mortgages (ARMs) as opposed to fixed-rate mortgages (FRMs). The stronger house-price response in a setting with ARMs can explain approximately 50 percent of the larger spending response in that environment. However, if long mortgage rates respond as strongly as short rates to changes in monetary policy, the aggregate demand response is remarkably similar in economies with FRMs and ARMs. The benefit that *all* existing mortgagors are affected by the lower mortgage interest rate under ARMs is roughly as important for aggregate spending as the benefit of persistently low rates of *new* mortgages under FRMs. The results highlight that paying close attention to both long mortgage interest rates and house prices can improve the assessment of the aggregate demand effect of monetary policy.

Overall, my findings show that a key driver of the response in aggregate consumption is the improved consumption smoothing of liquidity-constrained households who update their housing and mortgage choices. I conclude that including housing and mortgages in the analysis of monetary policy has qualitative implications for the transmission channels, and can have quantitative consequences for aggregate responses. Thus, a detailed understanding of the housing and mortgage markets is a valuable input in monetary-policy analysis.

The paper is organized as follows. In the remainder of this section I discuss how my findings relate to the literature. Section 2 describes the model. In Section 3, I proceed by calibrating the model to U.S. data, and I compare the model to the data along a range of relevant variables. In Section 4, I present and discuss my results. Section 5 concludes the paper.

1.1 Related literature

There are several empirical studies that suggest that mortgages play an important role in the transmission of monetary policy. In particular, households who experience changes in their mortgage interest payments adjust their consumption to a greater extent than other homeowners (Di Maggio et al., 2017; Flodén et al., 2020). Calza et al. (2013) show that in countries where variable-rate mortgages are more common, house prices and consumption respond more strongly to monetary policy shocks. Cloyne et al. (2019) conclude that the aggregate response to monetary policy is largely driven by mortgagors and households with little liquid wealth. The link between changes in house prices, mortgage debt, and spending is documented in, e.g., Mian et al. (2013) and Mian and Sufi (2014). I use all of these findings as motivating facts that I rationalize in my model. Moreover, I show that approximately half of the effect on aggregate demand comes from households who change their discrete choices. This mechanism is inherently difficult to capture empirically when the counterfactual is unobserved. Changes in shares of households who make different housing and mortgage transactions can be observed, but I show that these mask a rich heterogeneity.

There is an extensive literature that studies the transmission of monetary policy within the framework of dynamic stochastic general equilibrium models. Recently, the importance of incorporating heterogeneous agents with various degrees of liquid and illiquid wealth has been emphasized by Kaplan et al. (2018). In my model, owned housing is an illiquid asset that can be financed with a mortgage, and the costs associated with accessing housing equity are measured in the data. While Kaplan et al. (2018) find that the direct effects of interest rate shocks are small, I show that when including mortgages in the analysis the direct effects can be substantial. The interest rate exposure channel, highlighted in Auclert (2019), is the underlying cause of the heterogeneous income effects of households in my model. However, the focus of my paper is on the subsequent dynamics in the housing and mortgage markets, and how households' choices in these markets influence aggregate spending. The demand effect that I find to be driven by an improved consumption smoothing, is related to the work by McKay and Wieland (2021) and Attanasio et al. (2022) on lumpy durable consumption demand. Due to sizeable frictions and transaction costs associated with changing housing and mortgage holdings, changes in housing equity and optimal consumption can be rather lumpy, and monetary policy can affect the timing of adjustments. The severity of the liquidity constraints in the housing market is studied in Boar et al. (2021), who focus on implications for tax rebates and mortgage relief programs. Greenwald (2018) and Hedlund et al. (2017) incorporate housing and mortgages in large structural models and find that endogenous changes in house prices amplify aggregate responses to monetary policy shocks, something that I also find. Furthermore, my results show that extensive-margin portfolio updates among a small group of households are essential for the demand response, a mechanism that requires a rich heterogeneity among households. Specifically, in my model household characteristics are crucial for endogenous portfolio updates, whereas only aggregate states and states of the representative borrower matter in the model in Greenwald (2018). Moreover, by using a life-cycle model and by explicitly modeling the mortgage as a 30-year contract with either fixed or adjustable rate, I am able to realistically capture how constraining mortgage contracts are for different types of households, and ultimately how these households respond differently to interest rate changes.

The main contribution of this paper is to quantify the role of mortgage and housing choices, and the importance of changes in mortgage interest rates and house prices, for the transmission of monetary policy. The literature so far has focused on one such choice, namely, the choice of existing homeowners to take up a new mortgage, i.e., the refinancing channel of monetary policy, and has largely overlooked how housing choices are affected. Chen et al. (2020) document that cash-out refinancing is negatively related to the business cycle and played an important role for the debt and consumption patterns before and during the Great Recession. Wong (2021) highlights the refinancing channel and the importance of the age dimension for understanding refinancing choices. Beraja et al. (2018) show that the prevalence of mortgage refinancing is linked to house price growth, which in turn affects the spending responses to monetary policy. Berger et al. (2021) find that the importance of the refinancing channel is tied to the path of historical interest rates. Eichenbaum et al. (2022) emphasize that the distribution of savings from refinancing is a key determinant of the efficacy of monetary policy. My findings are complementary to these results. I corroborate findings that refinancing plays a central role for the transmission of monetary policy, but I also show that other transactions in the housing market are of quantitative importance. Concretely, I find that approximately 10 percent of the increase in aggregate demand stems from households who adjust their housing choice.

In terms of the structure of the mortgage market, I show that the aggregate response of consumption is larger when ARMs as opposed to FRMs are used, something that also, e.g., Garriga et al. (2017), Guren et al. (2021), and Wong (2021) find. My modeling framework is the most related to Wong (2021), and relative to her I make three main modeling contributions. I endogenize the house-price response to a monetary policy shock; it is costly to take up a larger mortgage, also when mortgages have adjustable rate; and mortgages in my model are 30-year annuities, the most common mortgage in the U.S. By endogenizing the response in house prices, it allows me to consider a number of counterfactual exercises. Specifically, I show that the different responses of house prices account for almost 50 percent of the difference in aggregate demand in the ARM versus the FRM setting, a finding that is empirically supported (see Calza et al. (2013)). In Wong (2021), on the other hand, it is assumed that there is no difference in the house-price response. I also show that the pass-through rate of monetary policy to mortgage rates is a key determinant of the aggregate demand response, in particular, through its impact on house prices. Finally, I find that house prices respond stronger to contractionary as compared to expansionary monetary policy shocks, contributing to an asymmetric response in aggregate spending.

2 Model

To study the aggregate demand implications of changes in mortgage and housing choices in response to a monetary policy shock, I use a heterogeneous-agent life-cycle model with a detailed modeling of mortgage contracts and the housing market. The setting represents a small open economy in which the interest rate is exogenous but where house prices and rental rates are equilibrium objects. In a given period, households choose to rent or own a house, the home size, the use of mortgage financing, saving, and consumption. House purchases are subject to transaction costs, and mortgage financing is restricted by down-payment and payment-to-income requirements. Furthermore, refinancing costs reduce the liquidity of housing equity. In the baseline setting, mortgages are modeled as 30-year contracts with fixed interest rate, which is the most commonly used mortgage in the U.S.[4]

2.1 Households

The model is in discrete time. Households enter the economy at age $j = 1$, which represents the first period of working life, and work until age J^{ret}. When each household i is born, it receives an initial endowment of liquid assets $b_{i,1}$, as in Kaplan and Violante (2014), and is allocated a permanent lifetime earnings state. In each year the household is endowed with earnings or retirement benefits $y_{i,j,t}$. For working-age households these depend on the aggregate earnings state in the economy Y_t at time t, the household lifetime earnings state, an age-specific component, and are subject to idiosyncratic permanent and transitory shocks. Following retirement, the benefits are in a fixed proportion R of the permanent earnings in the last period of working life, subject to a cap, where permanent earnings depend on the household lifetime earnings state and the past realizations of permanent earnings shocks. Earnings are given by

$$y_{ijt} = \begin{cases} Y_t\, \breve{y}_{ij} & \text{if } j \leq J_{ret}, \\ \breve{y}_{ij} & \text{otherwise,} \end{cases}$$

where $\breve{y}_{ij}$ is the household and age-specific component of earnings. The aggregate earnings state is normalized to one in steady state, and households do not expect any changes in aggregate income. However, a monetary policy shock may affect this variable. The income process is described in detail in Section 3.1. Households face an age-dependent probability of surviving to the next period $\phi_j \in [0, 1]$, and can live for a maximum of J periods. For ease of notation, I leave out the household subscript i in the rest of the model description.

There are three assets in the economy: owned housing h, mortgages m, and risk-free bonds b. Households realize utility from consumption c and housing services s, through a CRRA utility function with a Cobb-Douglas aggregator over consumption and housing

[4] In Section 4.2, I compare my findings to an economy where adjustable-rate mortgages are used instead.

services

$$U_j(c,s) = e_j \frac{\left(c^\alpha s^{1-\alpha}\right)^{1-\sigma}}{1-\sigma}.$$

The age-dependent parameter e_j is a utility shifter that accounts for changes in household size over the life cycle (see, e.g., Kaplan et al., 2020). Housing services can be rented at a unit price p_t^r or attained by owning a house that is purchased at a unit price p_t^h. If a household chooses to own a home of size h, there is a linear transformation of owned housing into housing services such that $s = h$.

Households derive warm-glow utility from bequests, similar to in De Nardi (2004).

$$U^B(q) = \upsilon \frac{\left(q + \bar{q}\right)^{1-\sigma}}{1-\sigma},$$

where υ denotes the weight that is attached to the utility from bequests, and $\bar{q}$ is a positive parameter that determines to what degree bequests are a luxury good. The amount of bequests q is given by the net worth of a household.

The illiquid nature of owned housing is characterized by transaction costs for both buying and selling a house, ς^b and ς^s, respectively. These are modeled as constant shares of the house value. Furthermore, a homeowner needs to pay a periodic maintenance cost δ^h, also proportional to the house value. All homeowners have access to long-term non-defaultable mortgages. The mortgage contract is modeled as the most commonly used mortgage in the U.S., i.e., a fixed-payment contract, where the mortgage is paid off over 30 years. It is possible to refinance a mortgage, but it is subject to refinancing costs. The length of the available mortgage contract is indicated by l, which is set to 30 when I parameterize the model. The number of periods left on a mortgage is then given by $N = \min(J - j, l - ma)$, where ma is the mortgage age. I thus assume that mortgages have to be repaid in l years or the number of years left until certain death, whichever is smaller.[5] The minimum required mortgage payment is an age, time, and mortgage-age

[5]This modeling choice is motivated by the fact that retirees tend to hold little debt and the terms of long-term mortgage contracts that are offered to retirees are often less favorable than those offered to working-age households.

dependent fraction $\chi_{j,t,ma}$ of the current mortgage balance m

$$\chi_{j,t,ma}\, m = \frac{r^m_{t^m}(1 + r^m_{t^m})^N}{(1 + r^m_{t^m})^N - 1} m, \qquad \text{for } r^m_{t^m} > 0,$$

where $r^m_{t^m}$ is the relevant mortgage interest rate of the contract. For a mortgage with fixed rate the relevant interest rate is the long-term rate at the time of the mortgage origination, i.e., $t^m = t - ma$. In steady state, the mortgage interest rate is constant, i.e., $r^m_{t^m} = r^m$, and is given by the risk free rate on bonds $r_t = r$ plus an exogenous credit spread κ, i.e., $r^m = r + \kappa$. To analyze a monetary policy shock, I impose unexpected changes to the real interest rates on bonds and mortgages that are estimated empirically. This is discussed in more detail in Section 4. New mortgage financing is restricted by a loan-to-value (LTV) requirement as well as a payment-to-income (PTI) cap. The LTV constraint is given by

$$m' \leq (1 - \theta) p^h_t h', \tag{1}$$

where θ specifies the required down-payment share of the house value $p^h_t h'$, and where prime indicates the current period choice of a state variable. The PTI requirement is modeled as

$$\chi_{j+1,t,1} m' + (\tau^h + \varsigma^I) p^h_t h' \leq \begin{cases} \psi Y_t n_j & \text{if } j \leq J_{ret} \\ \psi n_j & \text{otherwise,} \end{cases} \tag{2}$$

where τ^h and ς^I represent property tax and home insurance payments, respectively, and n_j is permanent income at age j.[6] Thus, ψ sets the maximum share of current permanent income that can be allocated to housing-related payments. These constraints need to be obeyed whenever a house is purchased or if a household chooses to refinance. In the latter case, the household has to pay a fixed refinancing cost ς^r, and a refinancing cost ς^r_p proportional to the mortgage size. A homeowner who does not refinance its mortgage

[6] When banks evaluate the payment capabilities of prospective mortgage holders, three main components include mortgage payments, property taxes, and home insurance costs. Home insurance costs are only included for calibration purposes of the PTI requirement, see Section 3.1, and are not included in the households' budget constraint.

needs to adhere to the minimum payment schedule

$$m' \leq (1 + r^m_{t^m})m - \chi_{j,t,ma}\, m. \tag{3}$$

The only nominal long-term contract in the model is mortgages. The model can therefore be solved in real terms, once accounting for that real mortgage balances of outstanding contracts change with the price level. The law of motion for the real mortgage balance for a household that chooses mortgage m' in period t is

$$m_{t+1} = \frac{m'_t}{1 + \Delta p_{t+1}}, \tag{4}$$

where $\Delta p_{t+1} = \frac{p_{t+1} - p_t}{p_t}$ is the change in the price level. In steady state, the price level is normalized to one and households do not expects any changes in prices.

In a given period, the state variable cash-on-hand x of a household is defined as follows,

$$x_{j,t,ma} \equiv \begin{cases} y_{j,t} + (1 + r_t)b - (1 + r^m_{t^m})m + (1 - \varsigma^s)p^h_t h - \delta^h p^h_t h - \Gamma_{j,t,ma} & \text{if } j > 1 \\ y_{j,t} - \Gamma_{j,t,ma} + b & \text{if } j = 1. \end{cases}$$

It consists of labor income or social security benefits, any savings from liquid bonds less the mortgage balance, including interest, the value of the house net of transaction costs, less maintenance costs and total tax payments $\Gamma_{j,t,ma}$.[7]

The total tax payments are made up by five different taxes

$$\Gamma_{j,t,ma} \equiv \tau^l y_{j,t} + \mathbb{I}^w \tau^{ss} y_{j,t} + \tau^c r_t b + \tau^h p^h_t h + T(\tilde{y}_{j,t,ma}).$$

A household pays local taxes on earnings given by the proportional tax rate τ^l.[8] All working-age households, as indicated by $\mathbb{I}^w$, also pay a social security tax τ^{ss}, proportional to earnings. Furthermore, there is a capital income tax τ^c that applies to all earned interest, and the property tax τ^h is paid by homeowners as a share of their house value. Finally, $T(\tilde{y}_{j,t,ma})$ captures the progressive federal labor income tax, where T is a non-

[7]The definition of cash-on-hand includes the net revenue from selling a house. This is only included for computational simplicity, and a household that stays in its house does not incur a transaction cost.

[8]Local labor income taxes are deductible, and are included in the model to ensure that high-earning households benefit more from using itemized deductions.

linear function that takes taxable labor income after deductions $\tilde{y}_{j,t,ma}$ as its argument. A household may deduct its mortgage interest payments, property taxes, and local labor income taxes. The federal income tax system is described in more detail in Section 2.3.

Let R, B, Ref, S denote the mutually exclusive and exhaustive cases where a household rents, buys a house, is a homeowner who refinances its mortgage, or is a homeowner who stays in their house and fulfills the minimum mortgage payment requirement, respectively. The dynamic household problem is described by the following Bellman equation where households discount future periods exponentially, with a discount factor β. Let $\mathbf{z} \equiv (h, m, ma, n, x)$, then for each $k \in \{R, B, Ref, S\}$,

$$V_{j,t}^k(\mathbf{z}) = \max_{c,s,h',m',b'} U_j(c,s) + (1-\phi_j)U^B(q') + \beta\phi_j \mathbb{E}_t \left[V_{j+1,t+1}(\mathbf{z}')\right]$$

subject to

$$c + b' + \mathbb{I}^R p_t^r s + \mathbb{I}^B(1+\varsigma^b)p_t^h h' + \mathbb{I}^{Ref,S}(1-\varsigma^s)p_t^h h + \mathbb{I}^{Ref}(\varsigma^r + \varsigma_p^r m') \leq x + m' \tag{5}$$

$$q' = b' + p_t^h h' - m' \tag{6}$$

$$s = h' \qquad \text{if } h' > 0$$

$$m' \geq 0 \qquad \text{if } h' > 0$$

$$m' = 0 \qquad \text{if } h' = 0$$

$$c > 0, s \in S, h' \in H, b' \geq 0,$$

where $\mathbb{I}^k$ are indicator variables that take the value of one for the relevant case and zero otherwise. The subscripts of the household-specific variables are dropped for notational convenience.[9,10] Equation (5) specifies the household's budget constraint, and equation (6) defines the bequests. The last four rows state a set of constraints including that a homeowner may not be a landlord and mortgages may only be used to finance owned housing. Rented housing services are available in discrete sizes contained in the ordered set $S = \{\underline{s}, s_2, s_3, ..., \overline{s}\}$. Owned housing is limited to a set H, which is a proper subset of S. Specifically, the smallest size $\underline{h}$ in H is larger than the smallest size in S, and above

[9]In steady state the t-subscripts are redundant.

[10]To ensure that bequests cannot be negative, I assume that they are collected at the end of the period before any interest accrue, and thus, the utility from bequests is not discounted, but the parameters of the bequest function are calibrated to match moments in the data.

and including $\underline{h}$ the two sets are identical.[11] A household that buys a house or refinances its mortgage also needs to fulfill the LTV and PTI requirements specified in equations (1) and (2). A homeowner that stays in the same house but does not refinance its mortgage needs to fulfill the minimum mortgage payment requirement in equation (3). The law of motion for mortgages follows equation (4). The solution to the household problem is given by

$$V_{j,t}(\mathbf{z}) = \max_k V^k_{j,t}(\mathbf{z}) \tag{7}$$

for $k \in \{R, B, Ref, S\}$, with the corresponding set of policy functions

$$\left\{c_{j,t}(\mathbf{z}), s_{j,t}(\mathbf{z}), h'_{j,t}(\mathbf{z}), m'_{j,t}(\mathbf{z}), b'_{j,t}(\mathbf{z})\right\}.$$

2.2 Housing markets

Housing services are available through owned housing as well as rental housing. The rental market consists of a unit mass of homogeneous rental firms f that provide rental housing to households. Firms operate in a competitive market and are owned by agents outside of the model. The required rate of return of the owners equals the after-tax return on bonds. In steady state, the house price is constant, i.e., $p^h_t = p^h$, and the equilibrium rental rate per unit of housing p^r is given by the following user-cost formula,

$$p^r = \left[1 - \beta_f + \beta_f \left(\delta^r + \tau^h\right)\right] p^h, \tag{8}$$

where $\beta_f = \frac{1}{1+(1-\tau^c)r}$ is the discount factor of the owners of the rental firms. Thus, the rental rate is such that the owners earn their required rate of return, after paying maintenance costs and property taxes. Both the maintenance cost and the property taxes are given by constant shares of the rental property value. The maintenance cost covers the depreciation of rental property $\delta^r p^h$, where $\delta^r > \delta^h$.[12]

[11] It is common in the literature to restrict the minimum house size available for owning, see, e.g., Cho and Francis (2011), Floetotto et al. (2016), Gervais (2002), and Sommer and Sullivan (2018).

[12] The assumption that the depreciation rate is higher for rental property than for owned housing is common in the literature (see, e.g., Piazzesi and Schneider, 2016), and is supported by the potential moral hazard problem in rental housing markets.

In the long run, i.e., in steady state, the supply of owned and rental housing are calibrated to match their respective demands, given the prices p^h and p^r. Specifically, the total stock of owned housing $\bar{H}$ is given by the total demand for owned housing

$$\bar{H} = \sum_{\mathcal{J}} \Pi_j \int_Z h_j(\mathbf{z}) d\Phi_j(Z),$$

and the total stock of rental housing $\bar{S}$ is provided by the total demand for rental housing

$$\bar{S} = \sum_{\mathcal{J}} \Pi_j \int_Z s_j(\mathbf{z}) d\Phi_j(Z) - \bar{H},$$

where Φ_j is the distribution of households' states at age j, and Π_j is the time-invariant fraction of the population of age j. In steady state, the house price is normalized, and the rental rate from equation (8) reflects that it is a fully competitive market with free entry and exit and zero profits. However, when considering how the house price and the rental rate respond in the short run to a transitory monetary policy shock, I assume fully segmented owned and rental housing markets, motivated by the findings in Greenwald and Guren (2021). They find that the owned housing and rental markets in the U.S. are characterized by a substantial degree of segmentation, close to full segmentation. Concretely, I assume that the supply of owned and rental housing are fixed in the short run at their respective long-run levels. The house price p_t^h then adjusts such that the demand for owned housing equals the steady-state supply. Similarly, the rental rate in each period p_t^r ensures that the demand for rentals equals the long-run supply.[13] Any short-run changes in profits for the rental firms due to a monetary-policy shock only affect the owners and not the households in the model. I discuss this further in Section 2.4.

2.3 Government

The government in the model has two main tasks: providing retirement benefits to the households and taxing the agents in a manner that reflects the U.S. tax code. Overall, the government runs a surplus, which it spends wastefully, or on matters that do not affect

[13] Housing markets can clearly be modeled in many different ways, in particular, to represent specific areas in the U.S. In Online Appendix B.5, I therefore provide a robustness analysis, in terms of how the rental rate responds to a monetary policy shock.

the agents in the model. Rental firms pay two taxes, property taxes in proportion to the value of the rental stock and capital income taxes on their profits. As discussed in Section 2.1, households pay five different taxes. Working-age households pay social security taxes, and all households pay local and federal labor income taxes. Additionally, there is a tax on earned interest on savings, and homeowners pay a property tax.

To capture the level of progressivity in the U.S. federal income tax schedule, I use a continuous and convex tax function as in Heathcote et al. (2017), where the argument is taxable earnings net of deductions $\tilde{y}$. The function is given by

$$T(\tilde{y}_{j,t,ma}) = \tilde{y}_{j,t,ma} - \lambda \tilde{y}_{j,t,ma}^{1-\tau^p},$$

where the parameters λ and τ^p control the level and the degree of progressivity in the tax system.

Taxable earnings are determined by labor income or retirement benefits less any deductions. Working-age households can choose to use an itemized deduction, a standard deduction, or not deduct anything, while retired households may only choose between the latter two. If a household chooses to use itemized deductions, it can deduct mortgage interest payments, property taxes, and local labor income taxes. The most favorable type of deduction depends on a household's earnings and the size of any payments that are deductible under the itemized specification. Specifically, a household chooses the type of deduction that minimizes $T(\tilde{y}_{j,t,ma})$, subject to

$$\tilde{y}_{j,t,ma} \in \begin{cases} \{\max(y_{j,t} - ID_{j,t,ma}, 0), \max(y_{j,t} - SD, 0), y_{j,t}\} & \text{if } j \leq J_{ret} \text{ and } ID_{j,t,ma} > SD \\ \{\max(y_{j,t} - SD, 0), y_{j,t}\} & \text{otherwise} \end{cases}$$

$$\text{where } ID_{j,t,ma} = r^m_{tm} m + \tau^h p^h_t h + \tau^l y_{j,t}.$$

ID denotes the deductible amount if a household uses itemized deductions, and SD is the tax subsidy available to households that opt for the standard deduction.

To summarize, the main components of the U.S. tax system relating to housing and mortgages are included in the model, i.e., imputed rents are not taxed, property taxes and mortgage interest payments are deductible, both itemized and standard deductions are available to households, and the earnings tax is progressive. By including these features, the model captures the heterogeneous benefits of owned housing and mortgages intrinsic to the U.S. tax system.

2.4 Equilibrium

To examine mortgage and housing choices in response to a monetary policy shock the goal is to model the cash flows of the shock as realistically as possible, both in terms of size and timing. To do so, I impose exogenously empirically estimated effects of a monetary policy shock on the real interest rates of bonds and mortgages, aggregate earnings, and the overall price level. I then let households decide on their consumption, saving in bonds, mortgages, and housing. Since the main focus of the paper is to study housing choices and their role for aggregate demand, I let the house price and the rental rate respond endogenously to the monetary policy shock. This allows me to conduct a number of experiments where house and rental prices are likely to respond differently. For instance, I study different mortgage environments, i.e., where contracts have adjustable instead of fixed rates, and examine the role of the house-price response. Moreover, I analyze the importance of the pass-through rate of monetary policy to long-term mortgage rates for aggregate demand. In the data, this pass-through varies significantly over time, see for example Del Negro and Otrok (2007) and Wong (2021). Since house prices are strongly linked to mortgage interest rates, it is critical to let house prices respond endogenously in these exercises. Furthermore, in the baseline analysis the response in the house price to a monetary policy shock can be compared with empirical estimates, which provides a validation exercise of the model.

With these aims, my modeling choices involve four main simplifying assumptions, all of which are made to focus as sharply as possible on the questions of the paper. Thus, for example, it is not a purpose of the paper to explain on a deeper level why the price level responds to a monetary policy shock. First, I exclude from the analysis the 5 percent richest households, which means that the net supply of financial assets is provided by agents outside of the model. Hence, I do not model financial intermediaries explicitly, and the financial asset market does not clear, i.e., the supply of mortgages exceeds the supply of bonds.[14] The implicit assumption is that financial intermediaries are either owned by foreigners, or the very wealthy households, who arguably behave according to their Euler equation, and do not respond much to changes in their income due to a monetary policy shock. This assumption critically allows me to study monetary policy by imposing the empirically estimated paths of the real interest rates of bonds and mortgages.

Second, rental housing is supplied by agents outside of the model. Thus, I assume that rental units are also either owned by foreigners or the very wealthy households. As such, any changes in profits for the owners of the rental firms are not affecting the households in the model. This assumption is motivated by the fact that few households in the bottom 95 percent of the net-worth distribution are landlords. In 2018, only 6.7 percent of all individual tax filers owned rental housing (Desilver, 2021). Hence, this modeling choice is made so as to generate realistic cash flows for the part of the household distribution that I study.

Third, to capture the delayed response in earnings to a monetary policy shock that we observe in the data, I impose an empirically estimated aggregate earnings path. This path is consistent with the estimated paths of the real interest rates that I use in the experiments, and ensures that the timing of changes in households' cash flows from earnings is well represented.

Fourth, an empirically estimated response of the price level to a monetary policy shock is used to deflate outstanding nominal mortgage balances, as described in equation (4) of the household problem. Again, the key goal is to have realistic real effects of the monetary policy shock. As an input in the analysis I therefore take the response in the price level, not to simultaneously model the pricing frictions that would lead to such a response. This allows me to solve the model in real terms.

To implement these assumptions, I first solve for a stationary equilibrium where all prices and earnings are exogenously given and constant over time. Specifically, the equilibrium house price in steady state is set exogenously, and the rental rate is given

[14] I make a back-of-the-envelope calculation of how the owners of financial intermediaries likely are affected by changes in the interest rate. If considering the first year, after a -100bp interest rate shock, the amount of new mortgages, for which the lower rate applies, is approximately equal to the amount of bonds. Thus, the financial intermediary is very well hedged against interest rate risk.

by equation (8). The dynamic programming problem is then solved recursively, and the steady state is found by simulating an economy where the households behave according to the solved for decision rules. In steady state, I calibrate the supply of owned and rental housing such that they equal the demand of the respective housing stocks from the simulation.

To analyze the effects of an interest rate shock, I then solve for a transitional equilibrium (of an unexpected monetary policy shock). Specifically, I feed in the empirically estimated paths of the real interest rate on bonds and mortgages, aggregate income, and the price level that are consistent with a monetary policy shock. Again, bonds and mortgages are supplied elastically such that supply equals demand at the exogenously given interest rates. Earnings are exogenous also in the transitional equilibrium, but the earnings of the working-age population are affected by the aggregate earnings state Y_t. The response in the price level is used to deflate the outstanding mortgage balances, as in equation (4). The paths of the interest rates, aggregate earnings, and the price level are further described in Section 4.1. To compute the transitional equilibrium, I solve for the paths of house and rental prices that clear the two housing markets in each period. Since I focus on the short-run implications of a transitory monetary policy shock, and construction of housing is rather slow, I assume that the supply of owned and rental housing is constant and equal to their respective steady-state levels.[15] Moreover, as described in Section 2.2, I assume fully segmented rental and owned housing markets. The equilibrium definitions are stated in Appendix A, and a more detailed description of the solution method, an assessment of its accuracy, and the discretization of the state space and the transitory earnings shocks, are provided in Online Appendix A.

3 Calibration

The model is parameterized to the U.S. economy in 1989 to 2019. I choose to use average data moments across many years in an attempt to avoid cyclicalities and to capture a steady state of the economy. Most of the parameter values are calibrated independently.

[15] This assumption may cause house and rental prices to respond too strongly to monetary policy shocks. However, this does not seem to be the case when I compare my price responses to findings in the empirical literature, see Section 4.1.

These include parameters that are either directly measurable in the data or where there is a standard in previous literature. The remaining parameters are calibrated jointly by minimizing the distance between several relevant equilibrium moments in the model and their data counterparts.

3.1 External model parameters

A summary of the independently calibrated parameters are found in Table I.

Demographics

A model period corresponds to one year. Households enter the economy at age 23 and work until age 65. The probability of dying at any age $(1-\phi_j)$ is set to match the observed and projected mortality rates for males born in 1950, in the Life Tables for the U.S., social security area 1900-2100 (see Bell and Miller (2005)). The maximum age J in the model is 83 years. The age-dependent equivalence scale parameters e_j are determined from the Panel Study of Income Dynamics (PSID) (PSID, 2017). The parameter values are set to the square root of the predicted values from a regression of family size on a third-order polynomial of age.

Preferences and interest rates

The parameter governing households' relative risk aversion σ is set to 2, which gives an intertemporal elasticity of substitution of 0.5. The real interest rate on risk-free bonds r is set to 0.028. This is consistent with the average yield on 30-year constant maturity nominal Treasury securities, deflated by the yearly headline Consumer Price Index (CPI). Between 1989 and 2019, this average real rate was 0.028 (the GS30 series, retrieved from FRED, Federal Reserve Bank of St. Louis, and the Bureau of Labor Statistics, Databases & Tables, Inflation & Prices). The mortgage spread κ is set to 0.011. This is given by the average yearly difference between the rate on 30-year fixed-rate mortgage commitments and the above nominal Treasuries, from 1989 to 2019. Thus, the steady-state mortgage interest rate is 0.039.

Parameter	Description	Value
σ	Coefficient of relative risk aversion	2
r	Interest rate, bonds	0.028
κ	Yearly spread, mortgages	0.011
τ^l	Local labor income tax	0.05
τ^c	Capital income tax	0.15
τ^{ss}	Payroll tax	0.153
τ^h	Property tax	0.01
l	Mortgage contract length	30
θ	Down-payment requirement	0.20
ψ	Payment-to-income requirement	0.177
δ^h	Depreciation, owner-occupied housing	0.03
ς^I	Home insurance	0.005
ς^b	Transaction cost if buying house	0.025
ς^s	Transaction cost if selling house	0.07
ς^r_p	Proportional refinancing cost	0.01
R	Replacement rate for retirees	0.50
B^{max}	Maximum benefit during retirement	0.61

Table I. Independently calibrated parameters, taken from the data or other studies
Note: The table lists calibrated parameter values, and where relevant, these are annual.

Taxes

The local labor income tax rate is determined by the average state and local labor income tax rate for households that itemize deductions, which was 5 percent in 2011 (Lowry, 2014). The tax rate on capital income is chosen to be the maximum rate that applies to long-term capital income for most taxpayers, which is 15 percent. The social security tax paid by the working age population, i.e., the payroll tax, is set to 15.3 percent of earnings. This rate captures the payroll taxes that are paid by both employees and employers (Harris, 2005). The property tax varies significantly across U.S. states. I choose a property tax rate of 1 percent, which is approximately the median rate in the American Housing Survey (AHS) for the 2009, 2011, and 2013 survey years.

Housing and mortgage markets

Mortgages have to be repaid over the course of 30 years, which is the most commonly used mortgage length in the U.S. Hence, l is set to 30. The minimum down-payment requirement θ in the model is 0.20. Below this threshold, mortgage lenders often require an extra insurance. Between 1978 and 1992, the average down payment of first-time buyers in the U.S. ranged from 11.4 to 20.5 percent of the house value (U.S. Bureau of the Census, Statistical Abstract of the United States (GPO), 1987, 1988, and 1994). The payment-to-income requirement ψ is set to 0.177, as in Greenwald (2018), but adjusted for the fact that mortgages and mortgage interest rates are real in the model.

The depreciation rate on owner-occupied housing δ^h is taken from Harding et al. (2007) and is set to 0.03. This value is the estimated median depreciation rate, gross of maintenance. The home insurance rate ς^I is equal to 0.005 of the house value. This figure is taken from the AHS, where the median property insurance payments correspond to approximately half of the median property tax payments.

The transaction costs for buying and selling a house, ς^b and ς^s, are set to 2.5 and 7 percent, respectively. These numbers are taken from Gruber and Martin (2003) who use median transaction costs in CES data to estimate the transaction costs in proportion to the house value. The part of the refinancing cost that is proportional to the mortgage size ς^r_p is set to 0.01, as in Boar et al. (2021).

Assets of newborns

In order to capture the positive relationship between wealth and earnings among young households, newborn households in the model are endowed with initial liquid assets $b_{i,1}$ conditional on earnings. The allocation is based on the method in Kaplan and Violante (2014). In the Survey of Consumer Finances (SCF), households of age 23-25 are divided into 21 groups based on earnings. Within each group, the share of households with asset holdings above 1,000 2019 dollars is calculated, along with their median asset values. The median asset holdings are then scaled by the median earnings of households aged 23-64. Within each of the comparable 21 groups in the model, ranked on initial earnings, the shares found in the SCF divide the households into low-earners who do not receive any initial assets, and high-earners who are allocated the median asset value consistent with that group, and rescaled by the median earnings of working-age households in the model.

Labor income and social security

The estimation of the process for the household and age-specific earnings $\breve{y}_{ij}$ follows Cocco et al. (2005). There is a deterministic life-cycle component of labor income, and in each period during working age, households' earnings are subject to idiosyncratic permanent and transitory shocks. For household i, of age $j \leq J^{ret}$, the log of labor income is given by

$$\log(\breve{y}_{ij}) = \alpha_i + g(j) + \eta_{ij} + \nu_{ij} \quad \text{for } j \leq J_{ret},$$

where α_i is a household fixed effect with the distribution $N(-\frac{\sigma_\alpha^2}{2}, \sigma_\alpha^2)$. The function $g(j)$ captures the deterministic life-cycle component of earnings, while η_{ij} and ν_{ij} are the permanent and transitory components, respectively. The transitory earnings shock ν_{ij} is i.i.d., with the distribution $N(-\frac{\sigma_\nu^2}{2}, \sigma_\nu^2)$. The permanent earnings risk is modeled as a random walk, where there are i.i.d. shocks ζ_{ij} with the distribution $N(-\frac{\sigma_\zeta^2}{2}, \sigma_\zeta^2)$, such that

$$\eta_{ij} = \eta_{i,j-1} + \zeta_{ij} \quad \text{for } j \leq J_{ret}.$$

In the model, the permanent earnings state n_{ij} consists of the three permanent components of labor income, i.e., $\log(n_{ij}) = \alpha_i + g(j) + \eta_{ij}$. In retirement, households receive a constant fraction R of permanent earnings in the last period of working life, subject to a cap B^{max}. Thus, there is no labor-income uncertainty in retirement.

$$\log(\breve{y}_{ij}) = \min\left(\log(R) + \log(n_{i,J_{ret}}),\ \log(B^{max})\right) \quad \text{for } j \in]J_{ret}, J]$$

The labor income process is estimated using data from the U.S. Bureau of Labor Statistics (BLS) and PSID, from 1970 to 1992, (BLS, 2020a,b; PSID, 2017). See Karlman et al. (2021) for a more detailed description of the data. A linear fixed-effect regression of the log of households' earnings on dummies for age, marital status, family composition, and education, is run to estimate the deterministic life-cycle profile. The components $g(j)$ are given by fitting a third-order polynomial to the mean predicted earnings by age from the regression. To estimate the variances of the permanent and transitory earnings shocks, I use a similar method as in Carroll and Samwick (1997). The variance of the fixed-effect shock is found by computing the residual variance of earnings that is left after accounting for the life-cycle component and the estimated variances of the permanent and transitory shocks, for households of age 23,

$$\sigma_{\alpha}^{2} = \mathrm{Var}\left(\log(\breve{y}_{i1}) - g(1)\right) - \sigma_{\zeta}^{2} - \sigma_{\nu}^{2}.$$

The estimated variances are presented in Table II.

Parameter	Description	Value
σ_{α}^{2}	Fixed effect	0.156
σ_{ζ}^{2}	Permanent	0.012
σ_{ν}^{2}	Transitory	0.061

Table II. Estimated variances

Note: The estimated variances for: the fixed-effect earnings shock that households are exposed to when they enter the economy, and the permanent and transitory earnings shocks that households are subject to before retirement. Estimated using BLS and PSID data (BLS, 2020a,b; PSID, 2017).

The replacement rate R for retirees is chosen to be 50 percent of permanent earnings in the last period of working life. This number is taken from Díaz and Luengo-Prado (2008). The maximum-benefit limit B^{max} is computed from Social Security Administration (SSA) data, and is equal to 0.61 in the model. This number can be evaluated relative to the mean of expected annual earnings during working life, which is normalized to one.

3.2 Endogenously calibrated parameters

The parameters that I calibrate endogenously by targeting relevant moments in the data are listed in Table III. The parameters are calibrated simultaneously, but the most relevant target moments for the respective parameters are listed in the table along with their values in the data and in the model. I use simulated method of moments where I minimize the sum of the squared relative deviations of the model moments and their data counterparts.

Parameter	Description	Value	Target moment	Data	Model
α	Consumption weight	0.75	Median house value-to-earnings	2.30	2.36
β	Discount factor	0.89	Median LTV	0.37	0.34
δ^r	Depreciation rate, rentals	0.04	Homeownership rate, age < 35	0.43	0.42
$\underline{h}$	Min. owned house value	0.2	Homeownership rate	0.68	0.71
ς^r	Fixed refinancing cost	0.1	Refinance rate	0.08	0.07
$\bar{q}$	Luxury of bequests	0.1	Homeownership rate, age 65-75	0.85	0.90
υ	Utility shifter of bequests	20	Mean net worth/mean earnings	1.45	1.24
SD	Standard deduction	0.07	Itemization rate, working age	0.49	0.49
λ	Level, tax function	0.98	Average marginal tax rates	0.13	0.13
τ^p	Progressivity, tax function	0.17	Distr. of marginal tax rates	See text	

Table III. Endogenously calibrated parameters

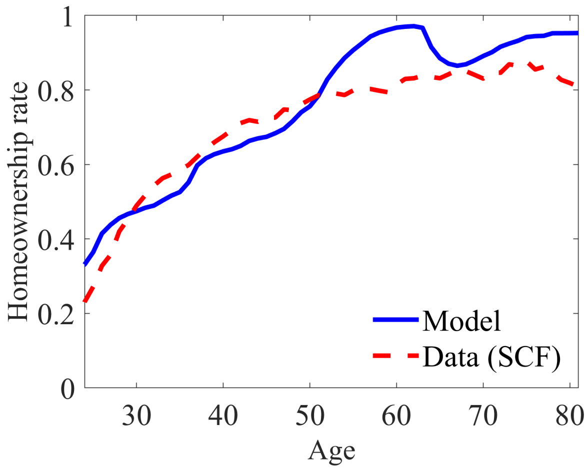
Note: The parameter values are shown in column three. Column five displays the relevant target moment value in the data, while column six shows the comparable moment value in the model when the listed parameter values are used. The values are annual when relevant. The minimum owned house size $\underline{h}$, the fixed refinancing cost, the luxury parameter in the utility function for bequests, and the standard deduction SD, can be assessed by comparing to the mean of expected annual earnings during working life, which is normalized to one. Median house value-to-earnings and median LTV are computed among homeowners.

Unless otherwise stated, the data moments are computed from the SCF, using pooled data over the 1989 to 2019 waves (SCF, 2023). Moreover, for each wave I drop the top 5 percent in terms of net worth, since the model is not well suited to capture the top tail of the wealth distribution. The parameter α in the utility function controls the share of expenses that is allocated to consumption as opposed to housing services. The target moment that is used to discipline this parameter is the median house value-to-earnings, conditional on owning, which is an indicator of the relative importance of housing costs compared to other expenses. The discount factor β affects borrowing and saving decisions, and is therefore calibrated by targeting the median LTV among homeowners. The benefit of buying a house instead of renting is in the model affected by the preferential tax treatment of owned housing as well as the difference between the depreciation rate of owned and rental housing. To calibrate the depreciation rate of rental housing δ^r, I use the homeownership rate among households younger than 35 as a target moment. The overall homeownership rate is used to discipline the size of the smallest house unit available to own $\underline{h}$. To account for the frictions in the mortgage market, I calibrate the fixed refinancing cost ς^r. In the steady state, the interest rate is constant and thus there is no reason to refinance to capture changes in the mortgage interest rate. The fixed refinancing cost is therefore calibrated by targeting the share of households that refinance while also extracting equity from the house. This data moment value is taken from Boar et al. (2021).

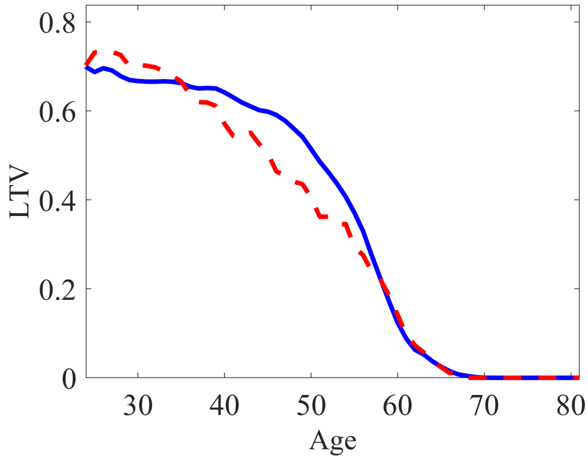
The two parameters of the utility function of bequests are disciplined by two target moments relating to savings. First, the parameter that captures the extent to which bequests are a luxury good $\bar{q}$ is calibrated by targeting the homeownership rate among old households, aged 65 to 75. Second, the parameter that determines the weight that is assigned to the utility from bequests υ is calibrated to match the mean net worth over mean earnings. Finally, I calibrate three parameters relating to the tax system. The level of the standard deduction SD impacts to what extent households use the itemized deduction, which in turn influences how households are differently affected by a change in mortgage interest rates. The standard deduction amount is used to match the itemization rate among the working-age population. The parameter λ that influences the level of the tax and transfer function $T(\tilde{y})$ is calibrated to match the average marginal tax rate in the economy; while the progressivity parameter τ^p is calibrated to approximate the distribution of households across statutory federal labor income tax brackets. The latter is done by computing the shares of households that are exposed to the different tax brackets. In the model, where the federal labor income tax rate is continuous, households are allocated to their nearest statutory bracket. I solve for the τ^p that minimizes the sum of the absolute values of the difference in shares in the model versus in the data. The data on the shares and the average marginal tax rate are taken from the Congressional Budget Office in 2005 (Harris, 2005), and the tax rates for the brackets correspond to the tax code from 2003 to 2012 (The Tax Foundation, 2013).

3.3 Model versus data

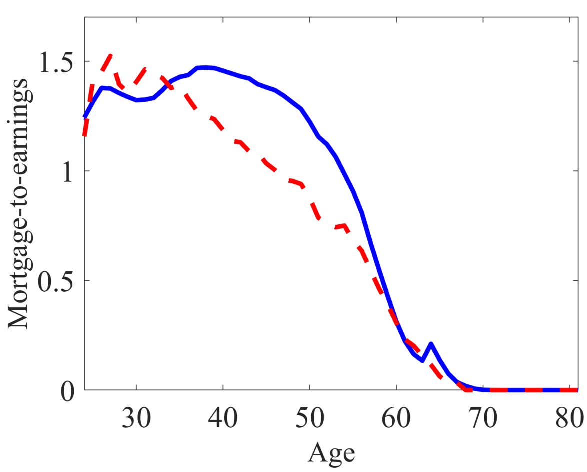
To evaluate how well the model reflects the data along dimensions that are not targeted in the estimation, I present a comparison between the model and the data for moments that are particularly important for how households respond to interest-rate changes. The effects of a change in the mortgage interest rate depend on the types of households that are homeowners and mortgagors, and how large mortgages different households use. In Figure 1, the life-cycle profiles of homeownership, median LTV, and median mortgage and housing relative to earnings are presented. The life-cycle patterns are clear: young homeowners are the most in debt and have the largest mortgage balances relative to earnings. Overall, the model successfully matches the life-cycle profiles computed from the SCF.



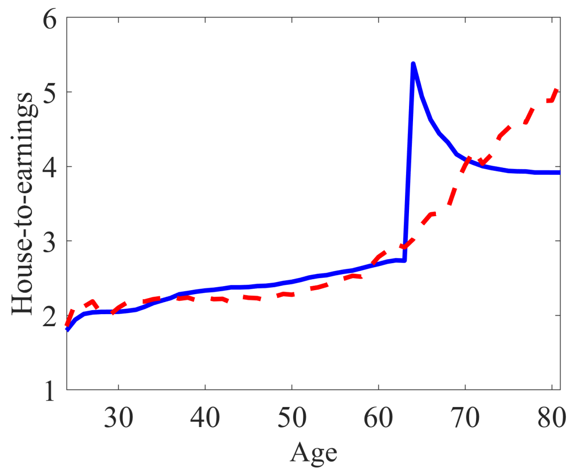
(a) Homeownership rate



(b) Median LTV



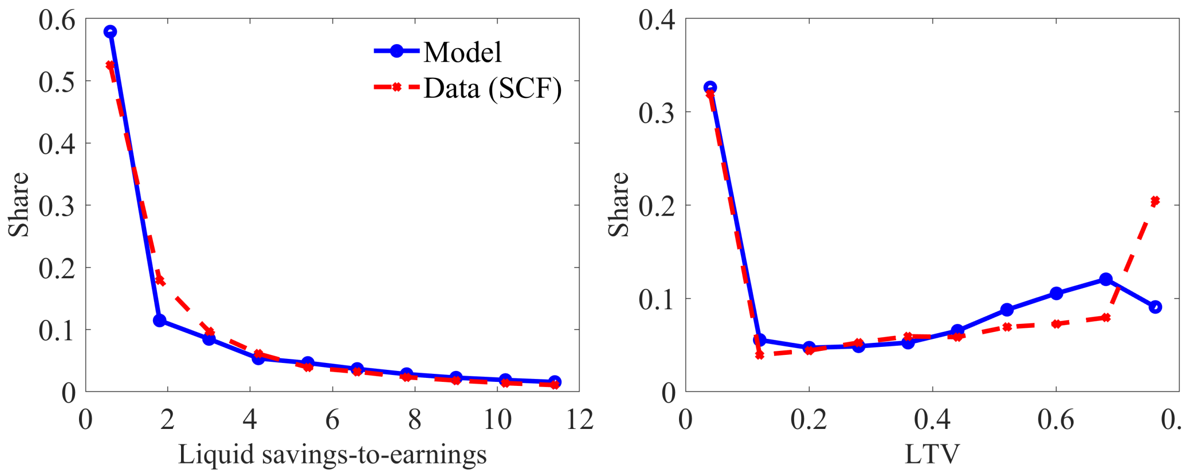
(c) Median mortgage-to-earnings



(d) Median house-to-earnings

Figure 1. Comparison between model and data: non-targeted life-cycle profiles
Note: (b) - (d) are computed among homeowners. Among retirees, retirement benefits are considered their earnings. Data refers to the Survey of Consumer Finances, for the survey years 1989 to 2019 (SCF, 2023).

The prevalence of liquidity-constrained homeowners impacts the importance of cash-



(a) Distribution, liquid savings-to-earnings

(b) Distribution, LTV

Figure 2. Comparison between model and data: non-targeted distributions
Note: Households are divided into ten bins according to the variable of interest and the share of households in each bin are displayed. The markers are placed at the midpoint of each bin. Only homeowners are considered. Data refers to the Survey of Consumer Finances, for the survey years 1989 to 2019 (SCF, 2023).

flow effects of monetary policy. A comparison of the distributions of liquid asset-to-earnings and LTV in the model versus the data, among homeowners, is displayed in Figure 2.[16] The figure demonstrates that significant shares of households have low liquid savings and high debt levels, both in the data and in the model. The distribution of liquid asset-to-earnings in the model matches the data remarkably well, given that liquid savings is not targeted in the calibration. If focusing on the lower part of the distribution, 33 percent of all households in the model have a liquid asset-to-monthly earnings ratio of less than 0.5, which is a threshold often used in the literature to approximate hand-to-mouth behavior, whereas this number is 38 percent in the SCF.

4 Results

When the central bank changes the interest rate it can affect the optimal portfolio allocation of households. Specifically, when there is a pass-through to mortgage interest rates, monetary policy can impact households' mortgage financing and housing choices. These types of portfolio adjustments often involve large transactions and changes in

[16] I define liquid assets as checking, savings, money market, and call accounts, prepaid cards, cash, bonds and bills, less any credit card debt balance.

households' liquidity, that in turn can influence aggregate consumption demand. Moreover, a change in the demand for owned housing leads to potentially important equilibrium effects on house prices. To shed light on the role of mortgage and housing choices for monetary policy transmission, I use the model presented in the previous sections and compute impulse response functions (IRFs) to an exogenous shock to the interest rate. I begin in Section 4.1 by quantifying the effects of changes in mortgage interest rates and house prices for aggregate spending, and I proceed by assessing how monetary policy affects aggregate demand through households' housing and mortgage choices. Moreover, I consider welfare implications and evaluate potential non-linearities and asymmetries in aggregate responses by examining shocks of different sizes and signs. In Section 4.2, I investigate the importance of the mortgage-market structure. Specifically, I evaluate how the pass-through rate of monetary policy to mortgage rates affects aggregate outcomes. Furthermore, I compare my main findings in the baseline setting with FRMs to a setting where ARMs are used instead.

4.1 The role of housing and mortgage choices for demand

To disentangle how housing and mortgage choices affect the aggregate demand response to monetary policy, let us first consider the different ways that a change in the interest rate affects households' consumption. In this model, there are three main transmission channels. First, the traditional channel of intertemporal substitution makes households want to consume more today and less tomorrow when the interest rate declines, as the relative price of consumption today compared to tomorrow decreases. Second, a decline in the interest rate affects the lifetime resources of households by affecting the return on savings and the interest cost of mortgages. These income effects impact different households differently. Households without or with a relatively small mortgage compared to savings, experience a negative income effect, whereas households with large mortgages tend to be positively affected by the decrease in the interest rate. Moreover, there are additional income effects resulting from the equilibrium effect of demand on earnings. Third, a change in the interest rate affects the portfolio allocations of households. As the return on liquid savings and the cost of mortgages change, there are equilibrium implications for house prices, and the optimal portfolio holdings of many households are altered. Along the intensive margin, homeowners may choose to reallocate their savings between liquid bonds and illiquid housing equity by paying off more or less on their mortgage. Importantly, households may also make extensive-margin adjustments, by buying and/or selling a house, and/or by taking up a new mortgage.

For households who are liquidity constrained, consumption responses to monetary policy are not necessarily reflecting their forward-looking Euler equation. For these households, changes in cash flows can lead to significantly different responses than implied by intertemporal substitution and income effects alone. Although changes in the return on savings and the interest payments on mortgages affect households' future cash flows, these changes in cash flows are for most households relatively small, and arise over time. Similarly, equilibrium effects of changes in demand tend to have a delayed impact on earnings. Much larger changes in cash flows occur instantly for households who adjust their housing and mortgage choices. If these households are constrained in their spending, the cash-flow effects can have real and direct implications for aggregate demand.

Portfolio adjustments endogenously make some households less liquidity constrained and others more constrained in their spending. Some homeowners may in response to the decline in the interest rate choose to access their housing equity by refinancing their mortgage or by moving to a new house. Some renters may choose to delay their house purchase, in particular if house prices are temporary elevated. On the contrary, some renters may advance their house purchase when the mortgage conditions are unusually favorable, straining their liquidity. Thus, to understand how the portfolio channel of monetary policy affects aggregate demand, a quantitative evaluation is necessary.

Monetary policy and house prices

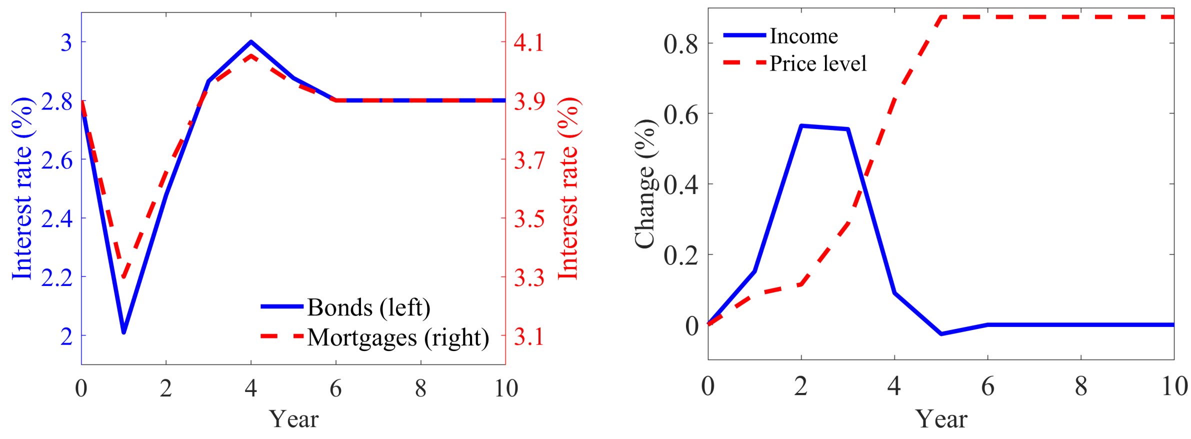
To study the effects of an interest rate shock, I feed in exogenous paths of the real interest rates on bonds and mortgages, aggregate income, and the overall price level. I use the empirically estimated path of the real interest rate from the identified Romer and Romer (2004) monetary policy shock in Auclert et al. (2020). I begin by considering a -100 basis points (bp) shock to the nominal interest rate. The expansionary shock translates into an immediate reduction of the real interest rate on bonds of approximately 80bp. For the long mortgage interest rate, I use the empirically estimated pass-through of 0.6 of a monetary policy shock to 30-year real mortgage rates, from Wong (2021). This is also broadly in line with empirical findings in Gertler and Karadi (2015) and Gilchrist et al. (2015).[17] Since mortgages have fixed rate, only the repayment plans of households who take up a new mortgage, i.e., those who buy a new house or choose to refinance a loan, adjust to the change in the mortgage interest rate. A household that takes up a new mortgage in the period when the interest rate shock occurs receives a mortgage interest rate of 3.3 percent for the next 30 years, instead of the steady-state rate of 3.9 percent.

In order to capture how households' housing and mortgage choices are affected by a change in the interest rate, it is crucial that the extent to which households are liquidity constrained in the data is well represented in the model. Moreover, it is important to include any potential changes in cash flows from monetary policy, since those impact households' liquidity. To incorporate a realistic timing of the equilibrium effect of demand on earnings, and to make the path of earnings consistent with the path of the real interest rates, I impose the empirically estimated path of aggregate income, also from Auclert et al. (2020). As described in Section 2.1, earnings of all working-age households adjust proportionally to the change in aggregate income. The paths that I impose exogenously are displayed in Figure 3. These are the real interest rate on bonds, the real 30-year mortgage interest rate, aggregate income, and the overall price level (which is only used to deflate outstanding mortgage balances).

To analyze how households respond, I start from the steady state of the model with an invariant distribution of households, and compute the non-linear IRFs to the "MIT shocks" to the real interest rates, earnings, and the price level as shown in Figure 3. Following Boppart et al. (2018), these IRFs can be used to provide a linearized solution to the model with aggregate risk, i.e., only first-order effects of aggregate shocks are considered, as with standard first-order perturbations. The shocks occur just before the households make any decisions, and there is an immediate endogenous adjustment of the paths of house prices and rental rates.

The unexpected decrease in the interest rates on bonds and mortgages affects the demand for housing as well as consumption. The equilibrium house-price and rental-rate

[17] In section 4.2, I consider alternative pass-through rates to mortgage interest rates.

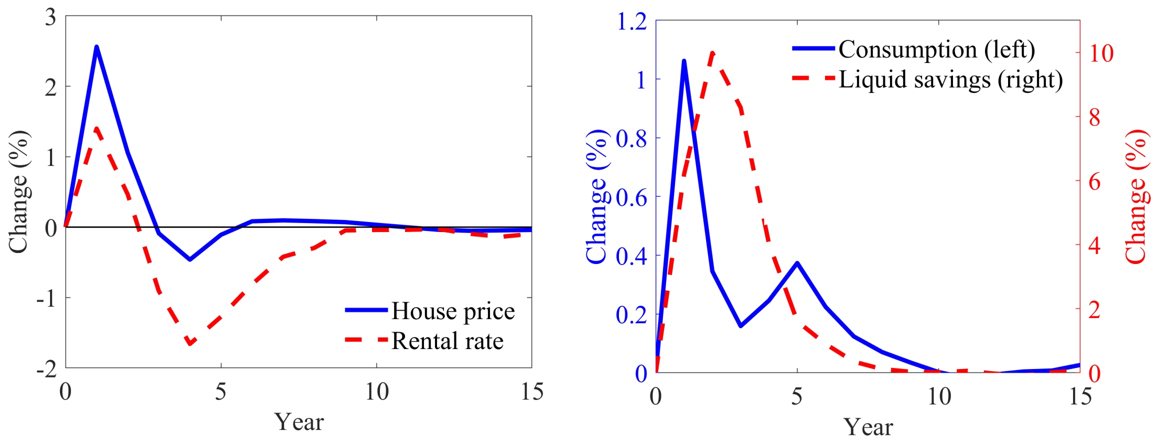


(a) Real interest rates (b) Aggregate income and price level

Figure 3. The monetary policy experiment: exogenous paths
Note: Paths of the real interest rates on bonds and mortgages, aggregate real income, and the price level. The paths follow an unexpected nominal interest rate shock of -100bp, where the paths of the real interest rate on bonds, aggregate real income, and the price level correspond to the estimated impulse response functions in Auclert et al. (2020). There is a 0.6 pass-through rate of the monetary policy shock to the 30-year mortgage interest rate, as estimated in Wong (2021).

paths that equalize demand and supply in these markets in all periods are presented in Figure 4a. By purchasing a house, a household can immediately transform the negative income effect from the lower return on savings into a benefit of lower interest payments on debt. As a result, the demand for housing increases following the expansionary interest rate shock, pushing up house prices. In the period of the shock, house prices increase by 2.6 percent, which is in line with empirical findings. Del Negro and Otrok (2007) estimate an upper bound of the house-price response that translates into approximately a 2.8 percent increase on impact in my setting. Iacoviello (2005) finds that the house-price increase is approximately 2 percent after one year, whereas Jarociński and Smets (2008) find a similar response but two and a half years after the monetary policy shock. More recently, Bartscher et al. (2022) also find a peak response of around 2 percent, but the response is rather slow. Paul (2020) shows that the one-year house-price response ranges from approximately 1.5 percent to 3.5 percent, depending on the time period considered. Over the past decade the response has been around 2.5 percent. It is reassuring that the benchmark model produces a house-price response that is consistent with empirical estimates, especially for the additional analysis where I adjust features of the mortgage market that potentially impact this response.

There is also a substantial increase in aggregate consumption demand and liquid savings, as presented in Figure 4b. In the period of the shock, consumption rises by approximately 1.1 percent. The higher liquidity is mainly a result of larger mortgage balances. In Figure 5, we see that the shares of households who buy a new house, refinance a mortgage, and move to a new owner-occupied house increase in response to the expansionary shock, and the average mortgage balances among these households also rise.[18] Figure 4 and 5 indicate that there is a comovement in house prices, mortgages, liquid savings, and aggregate consumption following the monetary policy shock. To quantify the role of changes in mortgage interest rates, house prices, and earnings, I compare the aggregate demand response in settings with different equilibrium price assumptions. Specifically, I compute consumption responses under the following conditions i) Mortgage interest rates, house and rental prices, and earnings are constant ii) House and rental prices and earnings are constant iii) Earnings are constant iv) All prices adjust. Table IV presents the aggregate consumption response in the period of the shock under the different assumptions. The full impulse response functions are displayed in Figure B.2 in Online Appendix B.



(a) House and rental prices

(b) Consumption and liquid savings

Figure 4. IRFs for house prices, rental rates, aggregate consumption, and liquids savings
Note: The impulse response functions follow a monetary policy shock of -100bp, with the corresponding changes to the real interest rates on bonds and mortgages, aggregate income, and the price level as displayed in Figure 3.

[18]Figure B.1 in Online Appendix B shows the IRF for the aggregate mortgage balance. After two years, the total outstanding mortgage volume is over 5 percent higher than in steady state.

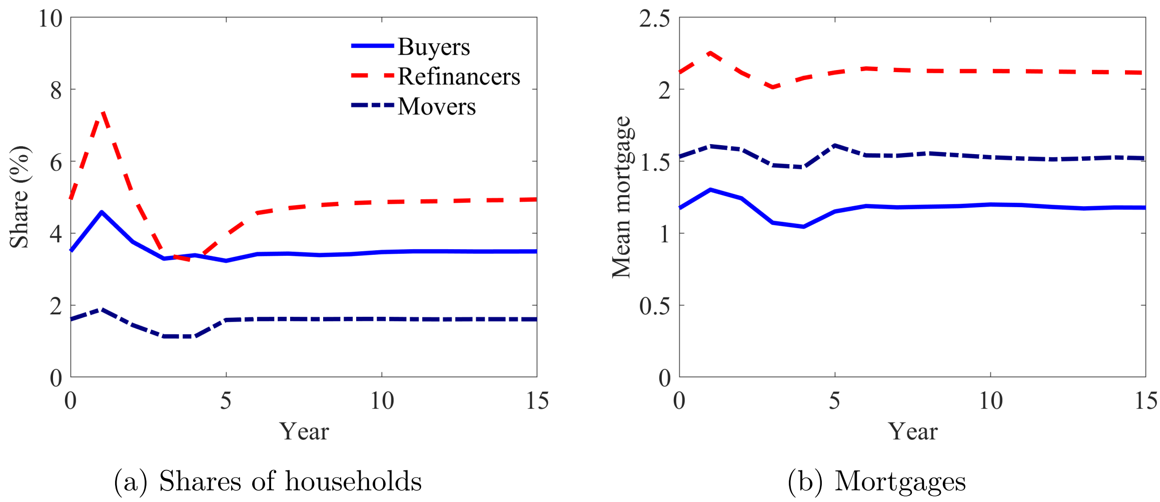


Figure 5. IRFs for shares making different discrete choices and mean mortgages

Note: IRFs for the shares of households who buy a new house, refinance a mortgage, and move to a new owner-occupied house, as well as the mean mortgage balance among these groups. The impulse response functions follow a monetary policy shock of -100bp, with the corresponding changes to the real interest rates on bonds and mortgages, aggregate income, and the price level as displayed in Figure 3.

	$\Delta\ r$	$+\ \Delta\ r^m$	$+\ \Delta\ p^h$	$+\ \Delta\ Y$
Δ aggregate consumption	0.05	0.35	0.71	1.06

Table IV. Consumption responses (%)

Note: Aggregate consumption responses under different equilibrium assumptions for mortgage interest rates, house and rental prices, and earnings. The deviations of consumption, in percent, are computed for the period when the interest rate shock occurs. The responses follow a monetary policy shock of -100bp, with the corresponding changes to the real interest rates on bonds and mortgages, aggregate income, and the price level as displayed in Figure 3, and with the endogenous responses in house and rental prices as presented in Figure 4a, when applicable.

Table IV illustrates that both the lower mortgage interest rate and the higher house prices amplify aggregate demand. When the monetary policy shock only transmits to the interest rate on bonds, but mortgage interest rates, house and rental prices, and earnings are kept constant, demand increases by a modest 0.05 percent. When allowing for mortgage interest rates to also be affected by the shock, the aggregate demand response is seven times larger. Moreover, by letting house and rental prices respond endogenously to the shock, the demand response is amplified by an additional 0.36 percentage points. Finally, by allowing earnings to increase, the initial response in aggregate demand increases by another 35bp, to 1.06 percent. Worth noting, the initial increase in earnings is relatively small, as seen in Figure 3b. Instead, the higher expected earnings in the future play a key role for the initial demand response, a point discussed further in the next section and in Online Appendix B.7.

The portfolio choice: housing, mortgages, and liquid savings

To understand the mechanisms behind the increase in aggregate demand we need to understand who the households are that respond strongly, and why they do so. I begin by analyzing the importance of households who update their discrete portfolio choices due to the interest rate shock. There are five mutually exclusive discrete choices available to the households: buy a house, refinance a mortgage, move to a different owner-occupied house, stay in a house and follow the amortization plan, and rent housing. To quantify the role of extensive-margin adjustments of households' portfolios, I compute the aggregate consumption response when not allowing households to change their discrete choice due to the interest rate shock. Specifically, households have to choose the same housing services and owned housing as they would have if prices and income did not change. Similarly, if they were to buy, refinance, move, stay, or rent in steady state, they cannot update these choices in response to the shock. Thus, households may adjust their consumption and saving in bonds and mortgages, but no extensive-margin portfolio adjustments are allowed. The resulting consumption response in the period of the shock is displayed in the fourth row of Table V. The third row shows the aggregate demand response if households can adjust their housing choices but only those who would have refinanced in steady state can and have to refinance when the shock occurs. The second row displays the consumption response if households have to make the same housing choices as in steady state but are free to update their refinancing choice.

There is a remarkably large difference in aggregate demand, if households are not allowed to make extensive-margin adjustments of their portfolios. In fact, without extensive-margin adjustments over 50 percent of the increase in aggregate spending is wiped out (an increase of 0.50 percent as compared to the equilibrium increase of 1.06 percent). Adjustments of housing choices explain roughly 20 percent of the amplification from discrete-choice updates, whereas refinancing accounts for the rest. Hence, updated housing choices contribute to approximately 10 percent of the increase in aggregate demand, whereas new refinancing explains about 40 percent.

To gain further insights into what types of discrete-choice updates contribute the most to the transmission of monetary policy, I examine consumption responses of households who make each possible update. Table VI presents the mean consumption response of households who make each discrete portfolio update, as well as the share of households of each type, in parenthesis.[19] The rows indicate the optimal discrete choice if the interest rate shock had not occurred, and the columns specify the optimal choice in the period of the shock. Hence, the main diagonal shows the responses for households who do not make an extensive-margin portfolio adjustment, whereas all the other positions show responses for those who make discrete updates. The last row displays the aggregates across all the optimal discrete choices had the interest rate shock not occurred.

Δ C, optimal portfolio choices	1.06 (1.00)
Δ C, steady-state housing choices	0.94 (0.89)
Δ C, steady-state choice to refinance	0.62 (0.58)
Δ C, steady-state discrete choices	0.50 (0.47)

Table V. Consumption responses (%)

Note: Aggregate consumption responses under different assumptions for extensive-margin portfolio adjustments. The deviations of consumption, in percent, are computed for the period when the interest rate shock occurs. The numbers in parenthesis are the responses divided by the response in the scenario with optimal portfolio choices. The responses follow a monetary policy shock of -100bp, with the corresponding changes to the real interest rates on bonds and mortgages, aggregate income, and the price level as displayed in Figure 3, and with the endogenous responses in house and rental prices as presented in Figure 4a.

A first key observation in Table VI is that only 7 percent of households make extensive-margin adjustments, although they account for more than 50 percent of the aggregate consumption response, as seen in Table V. Let us start by analyzing homeowners who choose to access their housing equity due to the shock. The fourth row of Table VI shows the consumption responses of households who would have stayed in their home and followed their amortization schedule if the interest rate shock had not occurred. When interest rates decrease and house prices increase some liquidity-constrained homeowners find it optimal to access their housing equity in order to increase consumption. Some of these households are liquidity constrained due to poor earnings realizations. Others are young homeowners who expect higher earnings in the future due to the upwards-sloping life-cycle profile of earnings, and therefore have little liquid savings. A homeowner can access their

[19] The shares may not add to 100 percent due to rounding.

	Buyers	Refinancers	Movers	Stayers	Renters
Buyers	0.0 (2.7)	-	-	-	-2.6 (0.8)
Refinancers	-	1.7 (4.7)	12.8 (0.1)	-11.5 (0.1)	0.6 (0.0)
Movers	-	6.5 (0.0)	1.6 (1.3)	6.7 (0.1)	-1.0 (0.2)
Stayers	-	12.4 (2.7)	7.2 (0.4)	0.5 (57.6)	12.9 (0.7)
Renters	-2.5 (1.9)	-2.0 (0.0)	2.8 (0.1)	-15.9 (0.1)	0.5 (26.5)
	-0.9 (4.6)	5.0 (7.5)	3.1 (1.9)	0.4 (57.9)	0.7 (28.2)

Table VI. Consumption responses and shares (%)

Note: Mean consumption responses of households who make each possible extensive-margin portfolio adjustment. The share of all households who make each portfolio update is in parenthesis, in percent. The deviations of consumption, in percent, are computed for the period when the interest rate shock occurs. The columns indicate the optimal choice to be a buyer, refinancer, mover, stayer, or renter in the period of the interest rate shock; whereas the rows indicate the optimal choice if the interest rate shock had not occurred. The final row shows the aggregates across all rows. The responses follow a monetary policy shock of -100bp, with the corresponding changes to the real interest rates on bonds and mortgages, aggregate income, and the price level as displayed in Figure 3, and with the endogenous responses in house and rental prices as presented in Figure 4a.

housing equity by either refinancing their mortgage (column 2), or by moving to a new home (column 3) or by becoming a renter (column 5). The consumption responses for all of these households are large and positive, as their extensive-margin portfolio adjustments increase their liquidity and allow for an improved consumption smoothing. Homeowners who choose to refinance their mortgage increase consumption by 12 percent, those who choose to move to a new house increase consumption by 7 percent, and those who become renters find it optimal to hike consumption by 13 percent, on average.

There are also homeowners who would have accessed their housing equity also without the interest rate shock, but who choose to do so in a different way, due to the shock. For these households the consumption responses vary more, as they are already accessing their illiquid savings regardless of the shock. Some households would have refinanced their mortgage if the shock had not happened, but when the shock occurs they choose to also update their housing choice and move to a new house, or move to a rental house. The average consumption of these groups increase by 13 percent and 1 percent, respectively, as seen in the second row of Table VI. Other homeowners would have moved to a new house had the interest rate shock not occurred, but now choose to stay in the current house and refinance their mortgage to access their housing equity. This group of households increase consumption by almost 7 percent. Finally, homeowners who would have become renters if it was not for the interest rate shock, but who now choose to stay in their house and refinance their mortgage or move to a different owner-occupied house, adjust their consumption by negative 2 percent and positive 3 percent, respectively.

Other homeowners choose to no longer access their housing equity, due to the shock. The consumption responses of these households are displayed in the fourth column of Table VI (rows 2, 3, and 5). Households who stay instead of move to a new house increase consumption by 7 percent, indicating that they are less financially constrained than if they had moved. On the other hand, those who no longer refinance their mortgage or do not become renters endogenously become more liquidity constrained, due to their portfolio choice, and decrease consumption significantly. The higher earnings, and the lower mortgage interest rate and higher house prices improve the current and future cash flows of these households to the extent that they no longer find it optimal to pay the refinancing and transaction costs to access their housing equity.

When it comes to renters, there are two potential extensive-margin portfolio adjustments: some renters delay and others advance their house purchase. On the one hand, some renters would have bought a house if it was not for the interest rate shock, but when house prices increase they choose to no longer do so. When these households do not have to finance the down payment and the transaction costs associated with buying a house, their liquid savings are larger. However, some of them still anticipate to buy a house later and they now have to pay a higher rental rate. Overall, in this group consumption decreases by 3 percent on average. On the other hand, some renters value highly the favorable mortgage conditions after the interest rate shock, and take the opportunity to buy a house when mortgage rates are low. As the down-payment requirement strains these households' liquidity, they also respond by decreasing consumption by 3 percent.

As mortgage and housing choices are associated with substantial changes in households' liquidity, this implies that a change in liquidity rather than liquidity per se is a key determinant of consumption responses. Figure 6 presents the mean consumption responses over deciles of liquid asset-to-earnings as compared to deciles of changes in liquid asset-to-earnings. The figure highlights that households with large liquid savings can also respond strongly to monetary policy shocks. In fact, liquid asset-to-earnings is a poor predictor of demand responses, since it is a poor predictor of extensive-margin portfolio adjustments. Changes in liquid asset-to-earnings, on the other hand, capture the strong demand effects of households who adjust their mortgage and housing choices in response to the interest rate shock.

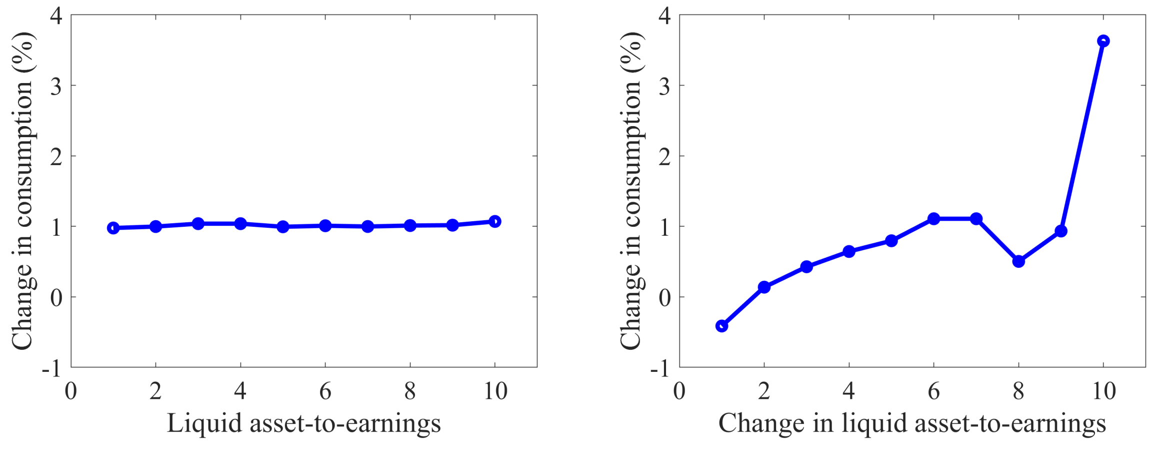


Figure 6. Consumption responses

Note: Mean consumption responses over deciles of liquid asset-to-earnings and change in liquid asset-to-earnings. The deviations of consumption, in percent, are computed for the period when the interest rate shock occurs. The responses follow a monetary policy shock of -100bp, with the corresponding changes to the real interest rates on bonds and mortgages, aggregate income, and the price level as displayed in Figure 3, and with the endogenous responses in house and rental prices as presented in Figure 4a.

To quantitatively assess the importance of the different types of extensive-margin portfolio adjustments, Table VII presents the relative contribution of each type for the overall demand response. Households who choose to refinance their mortgage due to the shock contribute the most to the increase in aggregate spending (43 percent, the sum of rows 3, 4, and 5, column 2). This is also evident in the third row of Table V, which shows that the aggregate demand response is reduced from 1.06 percent to 0.62 percent, if the steady-state choices to refinance are imposed. However, it is also clear that updated housing choices play an important role for the transmission of monetary policy. Households who had been homeowners if it was not for the interest rate shock, but who are now renting, contribute substantially to the aggregate demand response (6 percent in total, the sum of rows 1 and 4, column 5). In addition, households who move to a new house due to the shock account for 4 percent of the consumption response (the sum of rows 2 and 4, column 3). On the other hand, homeowners who decide to no longer access their housing equity do on average not contribute to the aggregate spending increase (the sum of rows 2, 3, and 5, column 4).

Extensive-margin portfolio adjustments directly affect cash flows of liquidity-constrained households, and allow for an improved consumption smoothing. Figure 5a and Figure B.3 in Online Appendix B.1 also reveal that many of the portfolio updates are advances of mortgage and housing choices. The initial increases in the shares of buyers, refinancers, and movers are followed by declines. The rent-to-own probability increases initially by around 30 percent, which is less than empirical findings in Dias and Duarte (2022), but is within approximately 1.3 standard deviations from their point estimate. There is also a small increase in the own-to-rent probability, whereas they find a slight decrease that is statistically insignificant. The combined effect translates into a muted response in homeownership. As seen in Figure B.3e, the homeownership rate increases slightly, in line with the results in Dias and Duarte (2022). After approximately ten years, the shares have returned to their steady-state levels. Thus, the portfolio channel partly works by affecting the timing of portfolio adjustments. This mechanism is similar to the transmission through timing adjustments of durable goods demand, as discussed in McKay and Wieland (2021) and relatedly in Attanasio et al. (2022).

Taking stock, the portfolio channel plays a significant role in the transmission of monetary policy. Specifically, a small group of households find it optimal to adjust their discrete housing and mortgage choices, and these households account for over half of the initial response in aggregate demand. Households who refinance their mortgage to access their illiquid wealth are particularly important, a channel that has been emphasized in previous literature. However, refinancing is not the only way through which homeowners can access their housing equity to increase consumption. Out of the contribution from discrete-choice updates, refinancing accounts for approximately 80 percent, whereas housing choices make up the remaining (see Table V). Hence, it is not only the frictions in the mortgage market that are important for the effectiveness of monetary policy, but the flexibility of the housing market is relevant as well. The combination of down-payment requirements, payment-to-income constraints, transaction costs when buying and selling a house, in addition to refinancing costs and amortization requirements, impact the transmission of monetary policy.[20]

[20] A more in-depth analysis of the role of the PTI requirement is presented in Online Appendix B.6. In short, the expansionary monetary policy shock makes the PTI constraint less binding for many households who want to take up a new mortgage, explaining approximately 10 percent of the increase in aggregate

	Buyers	Refinancers	Movers	Stayers	Renters
Buyers	0.00	-	-	-	-0.01
Refinancers	-	0.13	0.01	-0.01	0.00
Movers	-	0.00	0.03	0.01	-0.00
Stayers	-	0.43	0.03	0.26	0.07
Renters	-0.03	-0.00	0.00	-0.00	0.09
	-0.03	0.57	0.07	0.25	0.14

Table VII. Contributions to the response in aggregate demand

Note: Contributions to the aggregate consumption response, of households who make each possible extensive-margin portfolio adjustment, for the period when the interest rate shock occurs. The columns indicate the optimal choice to be a buyer, refinancer, mover, stayer, or renter in the period of the interest rate shock; whereas the rows indicate the optimal choice if the interest rate shock had not occurred. The final row shows the sum across all rows. The responses follow a monetary policy shock of -100bp, with the corresponding changes to the real interest rates on bonds and mortgages, aggregate income, and the price level as displayed in Figure 3, and with the endogenous responses in house and rental prices as presented in Figure 4a.

Although extensive-margin portfolio adjustments is an important transmission mechanism of monetary policy, most households do not update their discrete choices. The consumption responses of these households are in general more muted, and they tend to respond in more traditional ways to monetary policy. A detailed description of their behavior is relegated to Online Appendix B.2. Regarding the intensive margin of housing adjustments, buyers and movers who had bought or moved to a new house regardless of the monetary policy shock, reduce the size of the new home by 0.5 and 1.1 percent, respectively. Renters who rent irrespective of the shock, also reduce the size of their rentals by 0.5 percent on average. These adjustments follow from the higher house and rental prices.

Who gains and who loses from expansionary monetary policy?

Given the varying portfolios of households, monetary policy impacts households differently. This also implies that an expansionary monetary policy shock can be more or less beneficial for different households, and some may even be hurt by such a policy. Households with mortgages benefit from the lower mortgage rate and the deflated mortgage balances, whereas there is a negative effect through the lower return on any holdings of bonds. Moreover, the effects on house and rental prices affect different households differently

demand.

depending on their current house holdings and their expected future path of housing choices. In addition, working-age households benefit from the positive effect on earnings.

To examine the welfare effects of the 100bp expansionary monetary policy shock, I compute the ex ante compensating variation (CV). This measure states the one-time tax, as a share of cash-on-hand, that would make a household in the period of the shock, i.e., the first period of the transition, indifferent between the steady state and the scenario with the expansionary shock. Specifically, the CV for a household is defined by γ such that

$$V_{j,1}(h, m, ma, n, (1-\gamma)x) = V_{j,ss}(h, m, ma, n, x),$$

where $V_{j,ss}$ is the value function for a household of age j in steady state.

The welfare comparisons of course are partial-equilibrium results, so we should keep in mind that possible general-equilibrium effects as well as changes in profits that would fall on the 95 percent of households that we see here, are not reflected.[21] Figure 7 presents the distribution of CVs, and Table VIII provides the average household characteristics across groups with different welfare effects, as indicated by the red vertical lines in the figure. The figure clearly depicts that most households benefit from the expansionary monetary policy shock.

As expected, we see in Table VIII that welfare effects are positively correlated with LTV and negatively correlated with age and liquid savings-to-earnings. Welfare effects also tend to be higher for those who directly increase consumption due to the shock.[22] Approximately 15 percent of households expect to be negatively effected by the shock. These are predominantly retired households who do not benefit from higher earnings. They also have little debt and large savings in liquid assets, hence, they do not benefit from the lower mortgage interest rate but are rather hurt by the lower return on savings.

[21] General-equilibrium effects would depend on the additional assumptions I would need to make to close the economy. In fact, the reason to not make a general-equilibrium analysis is to carefully focus on these effects, and not make them dependent on how I would model the rest.

[22] Table B.I in Online Appendix B.3 shows that there is a less clear pattern of welfare effects across initial discrete-choice updates in response to the monetary policy shock.

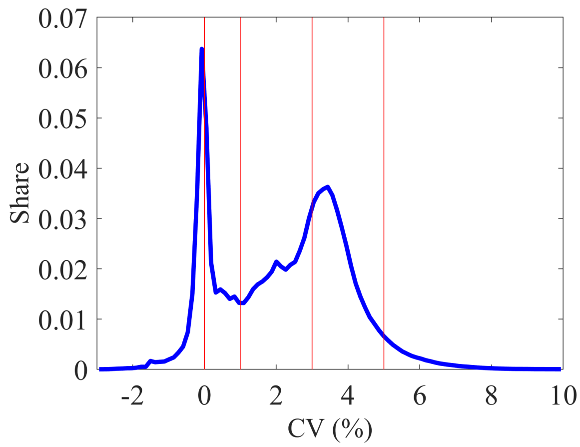


Figure 7. Distribution of CV

Note: Ex ante CV, expressed as share of cash-on-hand, in percent. The welfare effects are computed for a 100bp expansionary monetary policy shock. The corresponding changes to the real interest rates on bonds and mortgages, aggregate income, and the price level are displayed in Figure 3, and the endogenous responses in house and rental prices are presented in Figure 4a. The red vertical lines indicate a CV of 0, 1, 3, and 5 percent of cash-on-hand, respectively, and allocate the households into five groups based on their welfare effects. The mean household characteristics of the five groups based on these thresholds are presented in Table VIII.

	Group 1	Group 2	Group 3	Group 4	Group 5
CV (%)	-0.3	0.4	2.1	3.7	6.9
CV (2019 USD)	-376	611	2,377	3,352	5,141
Δ consumption (%), first period	-0.3	0.8	0.9	1.1	4.4
Age	70	67	49	37	35
Liquid savings-to-monthly earnings	17.1	5.6	4.4	3.2	0.4
House value	1.7	2.1	2.4	2.8	2.7
Mortgage age	11.1	11.0	6.3	4.2	4.0
LTV	0.02	0.08	0.36	0.64	0.67
Cash-on-hand	2.1	2.3	1.7	1.3	1.2
Share of population	0.15	0.15	0.31	0.35	0.05

Table VIII. Mean characteristics of households with different welfare effects

Note: The allocation of households into groups is based on their ex ante CV of a 100bp expansionary monetary policy shock, and is illustrated in Figure 7. Specifically, the households in groups 1 through 5 have CVs of ≤ 0, $(0, 1]$, $(1, 3]$, $(3, 5]$, and > 5 percent of cash-on-hand, respectively. When computing CVs in terms of dollars, I assume that the mean annual earnings, which is normalized to one in the model, is equal to 69,000 USD, which was the median household earnings in 2019. I use the median as a proxy, since the model is calibrated to match the bottom 95 percent of the wealth distribution in the data. The change in consumption is computed for the period when the shock occurs, and the other household characteristics are computed for the period of the shock but before any choices are made. Mean house value, mortgage age, and LTV are calculated among homeowners.

Implications for empirical analysis of consumption dynamics

It is inherently difficult to empirically assess how monetary policy affects transactions in the mortgage and housing markets, and in turn, link it to changes in consumption. The results in this paper highlight a challenge with empirical investigations of the transmission of monetary policy through discrete choices. When there are sizeable frictions and transaction costs associated with choices, optimal consumption can be rather lumpy. Hence, for the individual household, consumption in the current period is not necessarily a good predictor of consumption in the next period, and unfortunately, in the data we do not observe the counterfactual consumption, housing choice, or liquidity position of a household, had a shock to the interest rate not occurred.

For example, many homeowners who choose to stay in their home, due to the shock, but who would otherwise have moved to a different house, become less liquidity constrained on average as they no longer need to pay the transaction costs of buying, and increase consumption significantly. The findings in this paper indicate that these households contribute positively to the direct response in aggregate demand. In the data, these households have relatively large liquid savings, and relatively small changes in consumption when the interest rate shock occurs as compared to the period before the shock. However, the relevant measure is of course not how their consumption changes over time, but rather how it changes compared to the counterfactual outcome, had the shock not occurred. Moreover, in the data it is difficult to differentiate between households who make a discrete choice due to a shock, e.g., refinance their mortgage, and those who would have done so regardless. At best, we are able to observe the status of households prior and following a well-identified monetary policy shock, and how the shares of households of different status change. However, as shown in Table VI, the observed discrete choices following an interest rate shock, which are given by the columns, mask a rich heterogeneity in terms of consumption responses across the unobserved counterfactual choices, which are represented by the rows.

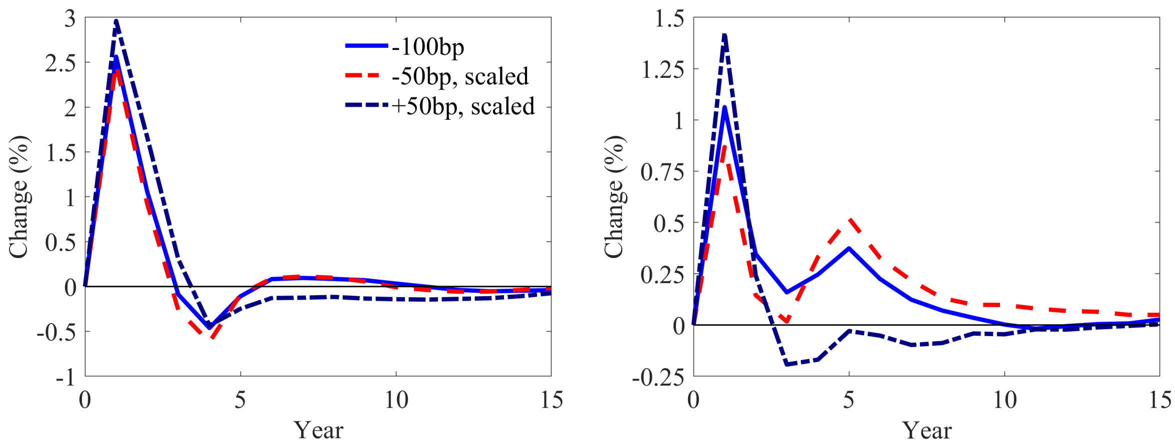
Nonlinearity and asymmetry in the aggregate demand response

The previous sections show that extensive-margin portfolio adjustments of a small group of households impact the aggregate spending response to monetary policy. The frictions in the housing and mortgage markets that generate the lumpy consumption behavior consist of the LTV requirement, the PTI constraint, the transaction costs when buying and selling a house, the refinancing costs, and the amortization requirement. With these relatively large frictions at play, does the size of the monetary policy shock matter for the importance of extensive-margin portfolio adjustments? Moreover, do contractionary shocks affect the economy in a similar fashion as expansionary shocks but simply in the opposite direction? To examine potential nonlinearities and asymmetries in the response to monetary policy shocks, I consider expansionary and contractionary shocks of half the size, i.e., 50bp shocks.

Figure 8 presents the endogenous response in house prices and the impulse response functions of aggregate demand to -50bp and +50bp monetary policy shocks, scaled by the shock size for ease of comparison with the -100bp shock. Let us first consider the expansionary shock of smaller magnitude. The figures convey that house prices respond linearly to changes in the interest rate, whereas there is a relatively smaller initial response in consumption to the -50bp shock. The second column of Table IX shows that discrete portfolio updates still account for more than half of the aggregate demand response. Similarly to the larger shock, refinancing explains roughly 80 percent of the contribution from discrete choices, whereas updated housing choices make up the rest.[23]

Although there are large costs associated with adjusting housing and mortgage holdings, small interest rate changes can still trigger such updates for households that are at the margin. As evident in the table, extensive-margin adjustments are still as important in explaining the response in aggregate demand. However, clearly, there are limits where the linearity breaks. For shocks approaching zero, extensive-margin adjustments should not play a role. At the other end of the spectrum, with increasingly large shocks the additional share of households that can improve their consumption smoothing by updating their mortgage and housing choices declines. The more muted response in consumption for

[23] There is also a small substitution effect, such that if refinancing is held fixed, housing choices become more important and vice versa.



(a) House prices

(b) Consumption

Figure 8. IRFs for house prices and aggregate consumption

Note: The impulse response functions follow unexpected expansionary and contractionary monetary policy shocks of different sizes. The corresponding changes to the real interest rates on bonds and mortgages, aggregate income, and the price level are illustrated in Figure 3 for the expansionary shock of 100bp. The responses are scaled by the shock size to be comparable with the -100bp shock.

	-100bp	-50bp	+50bp
Δ C, optimal portfolio choices	1.06 (1.00)	0.87 (1.00)	1.43 (1.00)
Δ C, steady-state housing choices	0.94 (0.89)	0.74 (0.85)	1.45 (1.02)
Δ C, steady-state choice to refinance	0.62 (0.58)	0.49 (0.56)	1.05 (0.74)
Δ C, steady-state discrete choices	0.50 (0.47)	0.38 (0.44)	1.06 (0.74)

Table IX. Consumption responses (%)

Note: Aggregate consumption responses under different assumptions for extensive-margin portfolio adjustments. The deviations of consumption, in percent, are computed for the period when the interest rate shock occurs. The numbers in parenthesis are the responses divided by the response in the scenario with optimal portfolio choices. The responses follow unexpected expansionary and contractionary monetary policy shocks of different sizes. The corresponding changes to the real interest rates on bonds and mortgages, aggregate income, and the price level are illustrated in Figure 3 for the expansionary shock of 100bp. The house-price responses are presented in Figure 8a. The responses are scaled by the shock size to be comparable with the -100bp shock.

the smaller shock follows from the smaller absolute change in house values. The housing equity for homeowners increases one-for-one with the rise in the house value, whereas the transaction costs are either fixed or increase linearly but only as a small fraction of the increase in the house value. Hence, for a smaller shock, adjustment costs eat up more of the freed up liquidity from discrete adjustments, leaving less for consumption.

When considering a shock of the opposite sign, i.e., a contractionary shock, one expects the unconstrained households to have symmetric responses. However, is this also true for the liquidity constrained? An increase in the interest rate and the associated decline in house prices and earnings reduce homeowners ability to smooth consumption in a similar way that an expansionary shock allows for an improvement. An important difference though is that the contractionary shock worsens the consumption smoothing of households that have a higher marginal value of current consumption, than those whose consumption smoothing improves following an expansionary shock. Moreover, the contractionary shock increases the share of liquidity-constrained households exhibiting hand-to-mouth behavior. As a result, both house prices and aggregate demand contract significantly more in response to an interest rate increase, than they grow in response to the corresponding decrease, as seen in Figure 8 and Table IX. Hence, this model provides mechanisms that generate results in line with the empirical findings in, e.g., Tenreyro and Thwaites (2016).

In terms of discrete-choice updates, these are largely used to improve consumption smoothing following an expansionary shock. This adjustment mechanism can to some extent also be used when households face a contractionary shock. For this reason, extensive-margin portfolio adjustments account for less of the aggregate demand response to a contractionary shock as compared to an expansionary shock, as seen in Table IX. In particular, updated housing choices contribute to a minor dampening of the fall in spending. However, refinancing still amplifies the response in demand, but it plays a smaller role when the shock is contractionary, explaining roughly one quarter of the decrease in aggregate consumption. The change in the share of refinancers in response to shocks of various signs is approximately symmetric, as seen in Figure B.3 in Online Appendix B.1. The symmetry follows from that there is always someone at the margin of refinancing. Hence, both increases and decreases in the interest rate affect the refinancing probability. In response to the contractionary shock, fewer households find it worthwhile to refinance, contributing to the decrease in demand. If forcing households to refinance, as if the shock did not occur, consumption would decrease less, but this is clearly suboptimal for the affected households.

4.2 Mortgage interest rates and transmission of monetary policy

The analysis of the portfolio channel of monetary policy transmission suggests that changes in mortgage interest rates and house prices are important drivers of the aggregate demand response. In the data, the pass-through rate of unexpected changes in the central bank's policy rate to long interest rates varies significantly over time.[24] To investigate the importance of the pass-through of monetary policy to long mortgage interest rates, I compare the baseline scenario with a 60 percent pass-through to three alternative settings. First, I assume that the long mortgage interest rate of an FRM is given by the geometric mean of the expected gross yearly mortgage interest rates, for the next 30 years, in line with the expectations hypothesis of the term structure. Second, I consider the scenario where there is 100 percent pass-through, such that the long rate responds as much as the short rate on bonds. Third, I study a setting where the interest rate of the mortgage contracts is short term, and thus, also adjusts in parallel with the rate on bonds. Hence, in the third setting I study the counterfactual where mortgages have adjustable instead of fixed rate.[25]

A comparison of the initial consumption response and the equilibrium house-price response for the different pass-through scenarios are presented in Table X, along with the responses under ARMs. The table confirms the strong link between the mortgage interest rate, house prices, and the aggregate consumption response. Marginal house buyers clearly prefer a lower mortgage rate, explaining the positive relation between the pass-through rate and the house-price response. It is also beneficial that the low rate persists, which causes house prices to rise more under FRMs with full pass-through than under ARMs. The higher house prices in turn benefit liquidity-constrained homeowners who access their housing wealth to increase consumption.

The pass-through rate to mortgage interest rates is not only informative for understanding the effectiveness of monetary policy, it is also an important determinant for the difference in the demand response between economies with FRMs as compared to

[24]This may be due to, e.g., changes in term premia. Work-in-progress by Berger et al. (2018) suggests state- and path-dependent pass-through of monetary policy to mortgage rates, and Scharfstein and Sunderam (2013) find varying pass-through from changes in concentration in the banking sector.

[25]A more thorough analysis and description of the setting with ARMs is presented in Online Appendix B.4.

	FRM geo avg	FRM 60% pass-through	FRM 100% pass-through	ARM
Δ C	0.45	1.06	1.36	1.38
Δ p^h	0.62	2.56	3.37	3.17

Table X. Consumption and house-price responses (%)

Note: Aggregate consumption responses and endogenous house-price effects under different assumptions for the pass-through of monetary policy to mortgage interest rates under FRMs, and under ARMs (with full pass-through). The deviations from steady state, in percent, are computed for the period when the interest rate shock occurs. The responses follow a monetary policy shock of -100bp, with the corresponding changes to the real interest rate on bonds, aggregate income, and the price level as displayed in Figure 3.

ARMs. In line with empirical findings, aggregate demand responds stronger with ARMs than in the baseline setting with FRMs (Calza et al., 2013). Much of the difference can be explained by the larger house-price response under ARMs. In fact, if imposing the equilibrium house-price response from the baseline economy with FRMs in the setting with ARMs, demand increases by 1.23 instead of 1.38 percent. Hence, the different house-price responses in these two settings account for close to 50 percent of the difference in the aggregate consumption response. However, mortgage markets with more adjustable-rate contracts do not necessarily imply a much stronger impact of monetary policy, but this depends on the pass-through to mortgage rates. When there is full pass-through of the monetary policy shock to the long interest rates of FRMs, the aggregate spending response is in fact very similar to that under ARMs.

These findings are also relevant for assessing the effects of unconventional monetary policy, suggesting that there are potentially large effects of quantitative easing. Specifically, if the central bank can affect long mortgage interest rates through their asset-purchase programs, both house prices and consumption respond strongly.[26] Moreover, the results shed light on the transmission mechanism through adjustments of both mortgage *and* housing choices in response to changes in long mortgage rates.

5 Concluding remarks

Over the past decades, there have been important developments in macroeconomic research that emphasize that different households respond very differently to changes in their environment, and that this can have implications for aggregate responses to policy

[26] Di Maggio et al. (2019) present empirical evidence on the refinancing channel of quantitative easing.

changes. Many households are liquidity constrained and respond strongly to changes in their cash flows. In this paper, I explore one channel through which monetary policy can directly influence households' cash flows, namely, by affecting their mortgage and housing choices. I construct a heterogeneous-agent life-cycle model to study how different households' mortgage and housing choices impact their spending, in response to changes in interest rates. Moreover, I quantify the role of changes in mortgage interest rates and house prices for the response in aggregate consumption to a monetary policy shock.

Although only 7 percent of households adjust their housing and mortgage choices in response to a 100bp expansionary monetary policy shock, I find that these choices account for approximately half of the response in aggregate demand. Most of the increase in consumption is driven by an improved consumption smoothing among constrained households, whose liquidity rises when they update their housing and mortgage portfolio. I also find that both changes in mortgage interest rates and house prices are crucial for the extensive-margin portfolio adjustments and in turn the aggregate spending response. As the reduction in the policy rate feeds into mortgage interest rates, there is an endogenous rise in house prices. Higher house prices increase the wealth of existing homeowners, allowing for an improved consumption smoothing among those who choose to access their housing equity by either refinancing, moving to a new house, or moving to rental housing. Furthermore, I show that the structure of the mortgage market impacts the effectiveness of monetary policy. The extent to which a monetary policy shock passes through to long mortgage interest rates is a key determinant of the response in house prices and, in turn, aggregate demand. This pass-through rate is also important for understanding differences in the house-price and aggregate consumption response in economies with fixed-rate versus adjustable-rate mortgages.

Appendices

A Equilibrium definitions

A.1 Stationary equilibrium

Households are heterogeneous with respect to age $j \in \mathcal{J} \equiv \{1, 2, ..., J\}$, owner-occupied housing $h \in \mathcal{H} \equiv \{0, \underline{h}, ..., \overline{h} = \overline{s}\}$, mortgage $m \in \mathcal{M} \equiv \mathbb{R}_{+}$, mortgage age $ma \in \mathcal{MA} \equiv \{1, 2, ..., l\}$, permanent earnings $n \in \mathcal{N} \equiv \mathbb{R}_{++}$, and cash-on-hand $x \in \mathcal{X} \equiv \mathbb{R}_{++}$. Let $\mathcal{Z} \equiv \mathcal{H} \times \mathcal{M} \times \mathcal{MA} \times \mathcal{N} \times \mathcal{X}$ be the non-deterministic state space with $\mathbf{z} \equiv (h, m, ma, n, x)$ denoting the vector of individual states. Let $\mathbf{B}(\mathbb{R}_{++})$ and $\mathbf{B}(\mathbb{R}_{+})$ be the Borel σ-algebras on $\mathbb{R}_{++}$ and $\mathbb{R}_{+}$, respectively, $P(\mathcal{H})$ the power set of $\mathcal{H}$, and $P(\mathcal{MA})$ the power set of $\mathcal{MA}$, and define $\mathscr{B}(\mathcal{Z}) \equiv P(\mathcal{H}) \times \mathbf{B}(\mathbb{R}_{+}) \times P(\mathcal{MA}) \times \mathbf{B}(\mathbb{R}_{++}) \times \mathbf{B}(\mathbb{R}_{++})$. Further, let $\mathbb{M}$ be the set of all finite measures over the measurable space $(\mathcal{Z}, \mathscr{B}(\mathcal{Z}))$. Then, $\Phi_j(Z) \in \mathbb{M}$ is a probability measure defined on subsets $Z \in \mathscr{B}(\mathcal{Z})$ that describes the distribution of individual states across agents of age $j \in \mathcal{J}$. Finally, denote the time-invariant fraction of the population of age $j \in \mathcal{J}$ by Π_j.

Definition 1. A stationary recursive competitive equilibrium is a collection of value functions $V_j(\mathbf{z})$ with associated policy functions $\{c_j(\mathbf{z}), s_j(\mathbf{z}), h'_j(\mathbf{z}), m'_j(\mathbf{z}), b'_j(\mathbf{z})\}$ for all j; prices (p^h, p^r); quantities of the total owned housing stock $\bar{H}$ and the total rental housing stock $\bar{S}$; and a distribution of agents' states Φ_j for all j such that:

1. Given prices (p^h, p^r), $V_j(\mathbf{z})$ solves the Bellman equation (7) with the corresponding set of policy functions $\{c_j(\mathbf{z}), s_j(\mathbf{z}), h'_j(\mathbf{z}), m'_j(\mathbf{z}), b'_j(\mathbf{z})\}$ for all j.

2. Given p^h, the rental price per unit of housing services p^r is given by equation (8).

3. The total quantity of owned housing is given by the total demand for owned housing[27]

$$\bar{H} = \sum_{\mathcal{J}} \Pi_j \int_Z h_j(\mathbf{z}) d\Phi_j(Z).$$

[27] I assume a perfectly elastic supply of both owner-occupied housing and rental units in steady state. This implies that supply always equals demand and markets clear.

4. The total quantity of rental housing is given by the total demand for rental housing

$$\bar{S} = \sum_{\mathcal{J}} \Pi_j \int_Z s_j(\mathbf{z}) d\Phi_j(Z) - \bar{H}.$$

5. The distribution of states Φ_j is given by the following law of motion for all $j < J$

$$\Phi_{j+1}(\mathcal{Z}) = \int_Z Q_j(\mathbf{z}, \mathcal{Z}) d\Phi_j(Z),$$

   where $Q_j : \mathcal{Z} \times \mathscr{B}(\mathcal{Z}) \to [0,1]$ is a transition function that defines the probability that a household at age j transits from its current state $\mathbf{z}$ to the set $\mathcal{Z}$ at age $j+1$.

A.2 Transitional equilibrium

Let $\Phi_{tr,j,t}(Z_t) \in \mathbb{M}$ be a probability measure defined on subsets $Z_t \in \mathscr{B}(\mathcal{Z})$ that describes the distribution of individual states across agents of age $j \in \mathcal{J}$ at time period t.

Definition 2. Given a sequence of the interest rate on bonds $\{r_t\}_{t=1}^{t=\infty}$, the interest rate on mortgages $\{r_t^m\}_{t=1}^{t=\infty}$, aggregate earnings $\{Y_t\}_{t=1}^{t=\infty}$, the overall price level $\{p_t\}_{t=1}^{t=\infty}$, and initial conditions $\Phi_{tr,j,1}(Z_1)$ for all j, a transitional recursive competitive equilibrium is a sequence of value functions $\{V_{j,t}(\mathbf{z})\}_{t=1}^{t=\infty}$ with associated policy functions $\{c_{j,t}(\mathbf{z}), s_{j,t}(\mathbf{z}), h'_{j,t}(\mathbf{z}), m'_{j,t}(\mathbf{z}), b'_{j,t}(\mathbf{z})\}_{t=1}^{t=\infty}$ for all j; a sequence of prices $\{(p_t^h, p_t^r)\}_{t=1}^{t=\infty}$; a sequence of quantities of total owned housing demand $\{H_t\}_{t=1}^{t=\infty}$ and total rental housing demand $\{S_t\}_{t=1}^{t=\infty}$; and a sequence of distributions of agents' states $\{\Phi_{tr,j,t}\}_{t=1}^{t=\infty}$ for all j such that:

1. Given prices (p_t^h, p_t^r), $V_{j,t}(\mathbf{z})$ solves the Bellman equation with the corresponding set of policy functions $\{c_{j,t}(\mathbf{z}), s_{j,t}(\mathbf{z}), h'_{j,t}(\mathbf{z}), m'_{j,t}(\mathbf{z}), b'_{j,t}(\mathbf{z})\}$ for all j and t.

2. The owned housing market clears:

$$H_t = \bar{H} \quad \forall t$$

$$\text{where} \quad H_t = \sum_{\mathcal{J}} \Pi_j \int_{Z_t} h'_{j,t}(\mathbf{z}) d\Phi_{tr,j,t}(Z_t) \quad \forall t$$

   and $\bar{H}$ is the total housing stock in steady state.

3. The rental housing market clears:

$$\begin{aligned} & S_t = \bar{S} \quad \forall t \\ \text{where} \quad & S_t = \sum_{\mathcal{J}} \Pi_j \int_{Z_t} s_{j,t}(\mathbf{z}) d\Phi_{tr,j,t}(Z_t) - H_t \quad \forall t \\ \text{and} \quad & \bar{S} \text{ is the total rental housing stock in steady state.} \end{aligned}$$

4. Distributions of states $\Phi_{tr,j,t}$ are given by the following law of motion for all $j < J$ and t:

$$\Phi_{tr,j+1,t+1}(\mathcal{Z}) = \int_{Z_t} Q_{tr,j,t}(\mathbf{z}, \mathcal{Z}) d\Phi_{tr,j,t}(Z_t),$$

where $Q_{tr,j,t} : \mathcal{Z} \times \mathscr{B}(\mathcal{Z}) \to [0, 1]$ is a transition function that defines the probability that a household of age j at time t transits from its current state $\mathbf{z}$ to the set $\mathcal{Z}$ at age $j + 1$ and time $t + 1$.

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