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Abstract

In order to analyze the transmission mechanism of monetary policy, a recent body of literature combines nominal rigidities with heterogeneous agent models. The key property of these models is that the income level of agents is heterogeneous. This paper quantifies the roles played by income level heterogeneity in the response of consumption to monetary policy shocks using U.S. household data. We show empirically that the response of consumption to expansionary monetary policy shocks is larger for high income households than low income households. This result cannot be explained by standard Aiyagari-Bewley-Huggett type heterogeneous agent models, where low income households have a higher marginal propensity to consume due to borrowing constraints. Empirical facts related to household characteristics suggest two potential channels: the presence of illiquid assets and heterogeneity in government transfers. Motivated by these empirical findings, we develop a model that incorporates illiquid assets and heterogeneity in government transfers. Simulations based on the model indicate that the presence of illiquid assets is essential for explaining the heterogeneous consumption response.

Keywords: Consumption; Household income; Monetary policy; Liquidity
JEL classification: E21, E52

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1 Introduction

Monetary policy analysis based on Heterogeneous Agent New Keynesian (hereafter, HANK) models has recently attracted growing interest from both academics and central bankers (e.g. Yellen (2016) and Kuroda (2017)). This is because, in contrast to representative agent models that have long been used as the standard model in the literature, these models provide new and seemingly important insights into the monetary policy transmission mechanism, such as large general equilibrium effects that arise from differences in marginal propensities to consume (MPC) across households (see Kaplan and Violante (2018)).

In spite of this growing interest in HANK models, which household characteristics matter most to its consumption response to shocks - the key piece of information to understand the transmission mechanism of monetary policy using HANK models - has not been fully explored. In the standard HANK model built up on Aiyagari-Bewley-Huggett,[1] liquid assets, the only assets available for household savings, play a key role. Households can insure against idiosyncratic income risk and smooth their consumption by decumulating liquid assets when a large negative income shock arrives. This implies that low income households, who are liquidity constrained due to borrowing constraints, exhibit the largest consumption response to transitory income fluctuations. On the other hand, the recent literature points out the importance of incorporating additional ingredients into the standard HANK framework. An influential paper by Kaplan and Violante (2014) highlights the role played by illiquid assets in their analysis of fiscal stimulus payments. Their paper argues that higher income households are also liquidity constrained because their assets are illiquid, causing them to exhibit a large consumption response to transitory income fluctuations.[2]

In this paper, we study the role of illiquid assets in explaining differences in consumption responses to monetary policy shocks across households with different income profiles.[3] More specifically, the standard HANK model built up on Aiyagari-

[1]Specifically, the basic heterogeneous agent incomplete market models developed by Aiyagari (1994), Bewley (1986) and Huggett (1993).

[2]These households, who hold little or no liquid assets despite owning sizable illiquid assets, are called "wealthy hand-to-mouth" households in Kaplan and Violante (2014).

[3]Although the implications of including illiquid assets are thoroughly analyzed by Kaplan and Violante (2014), it is meaningful to analyze their implications in the context of monetary policy shocks separately. This is because compared to fiscal stimulus payments shocks, such as those studied in Baxter and King (1993), monetary policy shocks directly affect the rates of return on various assets and heterogeneity in asset holdings of households can be an important transmission channel in HANK models. Note that a similar point is raised by Doepke and Schneider (2006). In particular, when monetary policy shocks have some impact on the capital income that is generated from holding illiquid assets, the implication of incorporating illiquid assets into the model in monetary policy analyses can be different from that in fiscal stimulus payment analyses.

Bewley-Huggett predicts that low income households will be the most responsive to monetary policy shocks because they face borrowing constraints. In the model, high income households hold liquid assets to smooth their consumption, exhibiting smaller responses to monetary policy shocks.[4] On the other hand, as shown by Kaplan and Violante (2014), when the assets that high income households hold are illiquid, both low and high income households can be liquidity constrained. Moreover, since the response of liquid asset returns and illiquid asset returns to monetary policy shocks can be different,[5] households' portfolios can exhibit heterogeneous returns depending on their compositions. This implies that it is not obvious whether low income households or high income households react more to a monetary policy shock.

In this paper, we address the question of which type of household - high income or low income - displays a greater responsiveness of consumption to monetary policy shocks. Firstly, we use the U.S. Consumer Expenditure Survey (hereafter, CEX) to empirically quantify the response of household consumption to monetary policy shocks by income level, based on the local projection method proposed by Jordà (2005).[6] Secondly, we develop a model that explains these empirical findings and quantitatively assesses which mechanisms play important roles in the heterogeneous consumption response by income level.

From the empirical analysis we find that the consumption response of high income households to an expansionary monetary policy shock is significantly larger than that of low income households. This result is at odds with the implications of the standard Aiyagari-Bewley-Huggett model, which predicts exactly the opposite. Thus, we relax the assumption of the standard Aiyagari-Bewley-Huggett model that households use only liquid assets to insure against idiosyncratic income risk. More specifically, we develop a model incorporating assets with different degrees of liquidity, motivated by the fact that high income households in the U.S. tend to own their homes.[7] Since buying and selling housing entails transaction costs, this fact suggests that

[4] More specifically, the consumption response depends on households' asset positions because monetary policy shocks change the return on assets. Low income households tend to be debtors and high income households tend to be creditors in the standard Aiyagari-Bewley-Huggett model. Since the losers from lowering interest rates are creditors and the winners are debtors, an expansionary monetary policy shock increases the consumption of low income households more when considering their liquid assets positions.

[5] For example, an expansionary monetary policy shock lowers the rate of return on liquid assets but increases the rate of return on illiquid assets, as in Kaplan et al. (2018).

[6] We divide households into three income categories: low, middle and high income. These households correspond to the lowest 1/3, middle 1/3, and highest 1/3 of households based on total real annual income before tax in each time period, respectively.

[7] Moreover, using the Survey of Consumer Finance (SCF), we find that high income households tend to hold more illiquid assets. This finding is not limited only to housing, but is also found in assets such as retirement accounts. The results are shown in appendix B.

the illiquid asset channel may be important.[8] The illiquid asset channel refers to the differences in consumption responses across households arising from the presence of illiquid assets, which changes households' portfolio choices regarding liquid and illiquid asset holdings. In addition, household-level data show that the composition of income is different between low income households and high income households. More specifically, the main source of income for high income households is labor earnings, while for low income households it is transfer payments. This is also at odds with the assumptions of the standard Aiyagari-Bewley-Huggett model, in which government transfers are homogeneous across agents. Since the response of income to monetary policy shocks can itself differ across the types of income, we also incorporate a heterogeneous transfer payments channel.[9] The heterogeneous transfer payments channel refers to differences in consumption responses across households arising from differences in the share of transfer payments in total income.

Motivated by these empirical findings, we incorporate illiquid assets and heterogeneous transfer payments into an otherwise standard Aiyagari-Bewley-Huggett model. Simulation results based on our model closely replicate our key empirical finding, namely the pronounced response of consumption among high income households to an expansionary monetary policy shock. The results also show that, quantitatively, illiquid assets play the dominant role. While the heterogeneous transfer payments channel also plays a role, its contribution is limited.

In the model, high income households hold more illiquid assets than low income households in equilibrium, partly due to the fact they can afford to pay the transaction costs. Holding illiquid assets amplifies the consumption response of high income households following a monetary policy shock due to the following two reasons. Firstly, the key features of illiquid assets are that they require transaction costs but yield higher rates of return. High income households choose to hold sizable amounts of illiquid assets and little or no liquid assets so that their portfolios yield higher returns. This causes high income households to become liquidity constrained and thus increases their MPC. Secondly, capital income and the present-value of assets increase more in response to an expansionary monetary policy shock when households hold illiquid assets compared to the case where they hold only liquid assets. Since illiquid assets yield higher returns than liquid assets following expansionary monetary policy shocks, an increase in income and wealth translates into a larger rise in consumption.

[8] See the model section for a detailed description of illiquid assets.

[9] For example, an expansionary monetary policy shock has a positive impact on real wages. On the other hand, real transfer payments might be considered as being independent from monetary policy shocks, as Cloyne et al. (2018) point out.

Related literature

This paper is related to three strands of the literature. The first strand covers empirical work quantifying the heterogeneous effects of monetary policy shocks on consumption and includes studies such as Cloyne et al. (2018) and Wong (2016).[10] In particular, Cloyne et al. (2018) find that households with mortgage debt increase their consumption more following a cut in the interest rate than renters and homeowners without debt do. Moreover, their paper argues that a change of mortgage or rental payments in response to monetary policy shocks alone might not be sufficient to explain the entire consumption response, suggesting that other transmission channels are also operating. On the one hand, our empirical findings are consistent with Cloyne et al. (2018) as our analysis shows that high income households are more likely to possess homes with mortgages. On the other hand, our paper differs from Cloyne et al. (2018) in the sense that, while Cloyne et al. (2018) conduct only an empirical analysis, we use a model to provide explanations of the empirical facts and conclude that illiquid assets may play a key role in households' heterogeneous consumption responses to monetary policy shocks.

The second strand of literature focuses on empirical work investigating the relationship between consumption inequality and the transmission of monetary policy and includes studies such as Coibion et al. (2017) and Inui et al. (2017). In particular, Coibion et al. (2017) investigate empirically whether monetary policy shocks increase or decrease income and consumption inequality in the U.S. We, on the other hand, explore which households are more responsive to monetary policy shocks and test the quantitative implications derived from our model using U.S. data. Our analysis is able to pin down which household characteristics are important to understand the transmission mechanism of monetary policy shocks on aggregate consumption.

The third strand of literature consists of theoretical work using HANK models and includes studies such as Auclert (2016), McKay et al. (2016), Hagedorn et al. (2018) and Kaplan et al. (2018).[11] Our paper is different from these studies in two respects. Firstly, we incorporate both illiquid assets and heterogeneous transfer payments into the heterogeneous agent model.[12] Secondly, previous studies often rely on simulation exercises exclusively and do not evaluate their models with the data by conducting empirical exercises. In contrast, we estimate the consumption response of households using micro-level data and propose a model that is consistent

[10]Wong (2016) focuses on the heterogeneity of indebtedness that arises from population aging and the role of refinancing in the transmission of monetary policy.

[11]See also Gornemann et al. (2016), Guerrieri and Lorenzoni (2017), Oh and Reis (2012), Luetticke (2015), Ravn and Sterk (2017), McKay and Reis (2016), Den Haan et al. (2017), Bayer et al. (2018), and Werning (2015) for heterogeneous household models. See Ottonello and Winberry (2018) for a heterogeneous firm model.

[12]Kaplan et al. (2018) incorporate illiquid assets, and Hagedorn et al. (2018) incorporate heterogeneous transfer payments into a HANK model. However, neither incorporates both.

with our empirical analysis. One contribution of our paper is to show empirically the need to incorporate illiquid assets into HANK models when conducting monetary policy analyses.[13]

This paper is organized as follows. Section 2 describes the empirical framework. Section 3 presents the empirical results regarding the consumption response of households by income group. Section 4 explains the details of our model as well as the calibration strategy employed. Section 5 discusses the results obtained from the model simulation and section 6 concludes.

2 Empirical framework

In this section we explain how we construct the semi-aggregate data series of household consumption by income level and present the econometric procedure for estimating the consumption response to monetary policy shocks for groups of different income levels.

2.1 Data source of consumption: Consumer Expenditure Survey

We construct the dependent variables using the Consumer Expenditure Survey (CEX), which contains comprehensive household-level consumption data. In the CEX, each respondent household is interviewed every three months over four consecutive quarters and the data are organized as a rotating panel, meaning that part of the sample is replaced every quarter. Therefore, instead of using standard panel estimation techniques directly on the data, we construct a semi-aggregate consumption data series for the estimation. We divide the sampled households into three income categories:[14] low, middle and high income.[15] In this analysis, low, middle and high income households correspond to the lowest 1/3, middle 1/3, and the highest 1/3 of households by real annual income before tax in each quarter, respectively.[16] The rationale for this grouping is as follows. Firstly, we set the thresholds so that

[13]Kaplan et al. (2018), incorporate illiquid assets into a HANK model, but focus on decomposing the direct and indirect effects rather than providing direct empirical evidence of whether or not the presence of illiquid assets is essential to monetary policy analysis.

[14]Our results are unchanged even when different degrees of disaggregation are employed for the analysis. We also study the case where households are divided equally into five income groups instead of three. In this case, the highest income group still exhibits the largest consumption response to monetary policy shocks, while the second and third highest groups exhibit similar responses.

[15]Households report the amount of income received in the past twelve months.

[16]Similar categorization is used in Aguiar and Bils (2015). Also, our result is robust to the way that households are grouped. Estimation results are little changed, for example, if we divide households with a specific income level such as 30,000 dollars and 70,000 dollars.

the number of households in each income group is not too small relative to other groups. Since the household-level CEX data are very volatile, small samples can lead to large estimation uncertainty. Secondly, we set the thresholds so that households display similar characteristics within each income group. This is important since, as described in the section 3.2, the transmission of monetary policy shocks depends on household characteristics such as the source of income and housing tenure.

We follow the procedure used in Coibion et al. (2017) to clean the data and construct household-level consumption before aggregating. In the first step, we restrict the sample used in the empirical analysis by eliminating households who report food expenditure as zero and those with negative expenditure. Next, we calculate each household's consumption as the sum of non-durables expenditure, services expenditure and expenditure on durable goods and deflate it using the Consumer Price Index. As a result, our analysis contains 235,587 households, which is 91% of the total sample during the period 1980Q1 to 2008Q4.[17]

2.2 Empirical specification

To estimate the effect of monetary policy shocks on the consumption of different income groups, we use the local projection method proposed by Jordà (2005). As discussed in the literature, misspecification errors can be compounded with the more distant horizons in the impulse responses estimated by commonly-used Vector Autoregressions (VARs). In contrast, local projection provides estimates that are more robust to misspecification of the lag structure since it estimates the distant horizons directly and does not involve iterations. Following Coibion et al. (2017) and Tenreyro and Thwaites (2016), who employ the local projection method to estimate the effects of monetary policy shocks, we estimate the following equation

$$y^i_{t+h} = \alpha^i_{0,h} + \alpha^i_{1,h}\Lambda_t + \beta^i_h \epsilon_t + \gamma^i_h x^i_t + u^i_{t,h}, \tag{1}$$

where, y^i_{t+h} is the h-period ahead log of consumption of income group i, Λ_t is a time trend, ϵ_t is a monetary policy shock, x^i_t is a vector of control variables which includes the lagged dependent variable,[18] the federal funds rate and seasonal dummies. In choosing these variables, we follow Tenreyro and Thwaites (2016). Parameters $\alpha^i_{0,h}$, $\alpha^i_{1,h}$, β^i_h and γ^i_h are to be estimated. $u^i_{t,h}$ is the regression error term.

Under this specification, the cumulative impulse response to a monetary policy shock for income level i at time horizon h is calculated as $\sum_h \beta^i_h$. The standard

[17] Appendix A describes the methodology used to construct the consumption data in more detail and discusses the robustness of our empirical results to underreporting issues in the CEX.

[18] We calculate the optimal lag for each time horizon h and income level i using the Akaike Information Criterion (AIC).

errors are calculated by the Driscoll and Kraay (1998) method. This method allows us to make appropriate adjustments to the standard errors when the residuals are correlated not only among dates t but also across different horizons h.[19]

2.3 The identification of monetary policy shocks

To identify monetary policy shocks, we follow the narrative approach of Romer and Romer (2004). One advantage of extracting the series of shocks following the approach of Romer and Romer (2004) is that the shocks extracted in this way are considered to be orthogonal to the Fed's information set, so that they can be treated as exogenous monetary policy shocks. More specifically, monetary policy shocks are obtained by estimating the equation below:

$$\Delta FFR_t = \beta X_t + \epsilon_t, \tag{2}$$

where ΔFFR_t is the actual change in the federal funds rate at each FOMC meeting. X_t is a vector of control variables (such as the Greenbook forecast change of real output, GDP deflator, and the unemployment rate), and the estimated residuals $\hat{\epsilon}_t$ are the monetary policy shocks identified using the method of Romer and Romer (2004). We restrict the sample to the period from 1980Q1 to 2008Q4 in order to avoid the period when monetary policy reached the zero lower bound.

3 Empirical results

In this section, we examine whether the assumptions imposed by the standard Aiyagari-Bewley-Huggett model are consistent with the data and then study whether the response of consumption to a monetary policy shock in the model agrees with the data.

3.1 Household characteristics of each income group

The basic assumptions of the standard Aiyagari-Bewley-Huggett model are that households use liquid assets to insure against idiosyncratic income risk and that government transfers are homogeneous across households. As one might expect, however, these assumptions do not necessarily agree with the data. Namely, not all household assets are liquid and the share of government transfers in households' income is markedly different between high and low income households.

[19] We use the Delta method when calculating the standard errors of the cumulative coefficients that are obtained from the equation above.

Housing tenure

Figure 1 shows the housing tenure of households by income group.[20] The figure shows that more than half of households own thier homes as mortgagors or outright owners. Housing can be considered to be an illiquid asset because the purchasing and selling of homes entails transaction costs.[21] The results thus indicate that households can hold illiquid assets and that by purchasing housing, high income households as well as low income households can face liquidity constraints. This observation is at odds with the assumption that households hold only liquid assets.

Moreover, Figure 1 shows that housing tenure is clearly different between low income households and high income households. On the one hand, around half of low income households live in rented homes, while the percentage of households living in homes that they own is relatively limited. On the other hand, the percentage of high income households who live in homes that they own is approximately 80%.[22] In particular, the ratio of the households living in homes with a mortgage clearly increases with income. We complement the analysis with a second data set on household positions regarding the illiquid assets from SCF, which is shown in appendix B.

Income source

Figure 2 shows the source of income by income group.[23] The figure shows that there exists large heterogeneity in income sources between high income households and low income households. Specifically, for high income households, more than 80% of income comes from labor earnings and less than 5% from transfer payments. On the other hand, around half of the entire income of low income households comes from transfer payments and labor earnings contribute approximately only 40%.[24]

[20]The data used in Figure 1 come from the CEX. The sample period is 1980Q1 to 2008Q4. The results are stable over the entire sample period. For example, even if we use only the earlier half of sample period, from 1980Q1 to 1994Q4, the shares of households living in homes with mortgages are 16%, 33%, and 62% for low, middle and high income households, respectively. These are very similar to the shares shown in Figure 1.

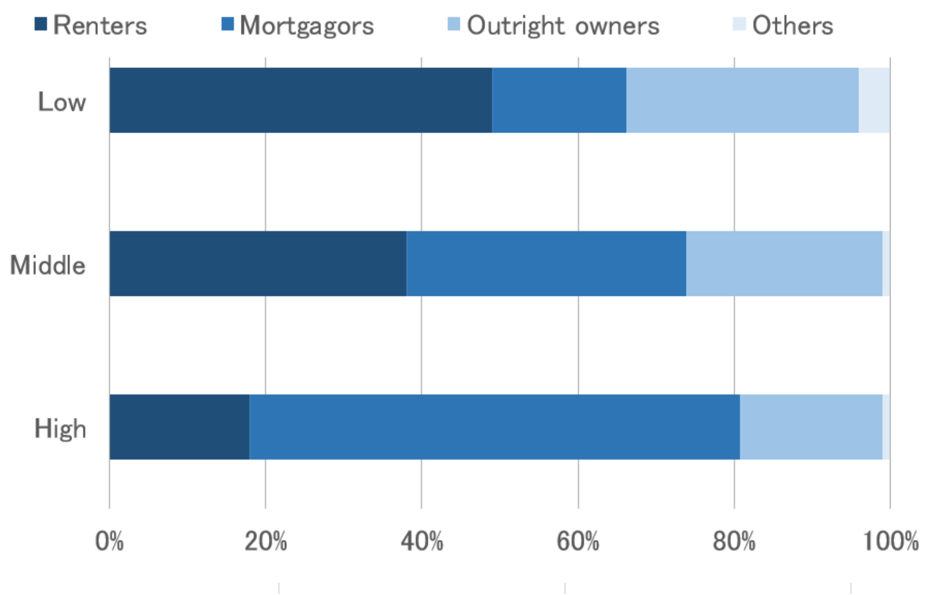
[21]For example, Kaplan and Violante (2014) employ a model that introduces housing as an illiquid asset.

[22]Segal and Sullivan (1998) also argue that the home ownership rate increases with household income.

[23]The numbers in the figure are the sample average of the data collected in the CEX. The sample period is 1980Q1 to 2008Q4. The figures are stable over the entire sample period. For example, even if we use only the first half of the sample period, from 1980Q1 to 1994Q4, the income shares of transfer payments in total income are 47%, 15%, and 4% for low, middle and high income households, respectively. These are very similar to the shares shown in Figure 1.

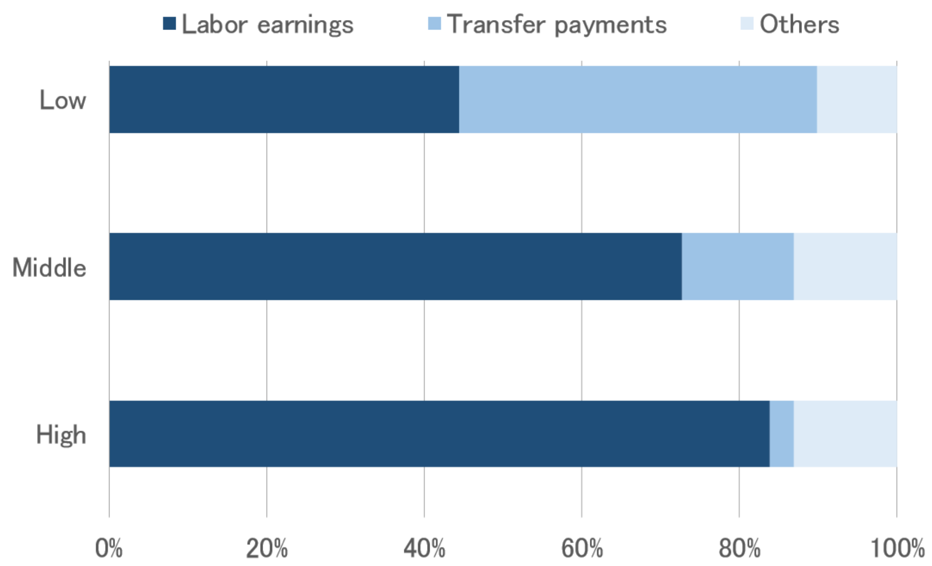
[24]See, for example, Diaz-Gimenez et al. (2011) who argue that the income share of transfer payments decreases with household income in the U.S.

Figure 1: Housing tenure



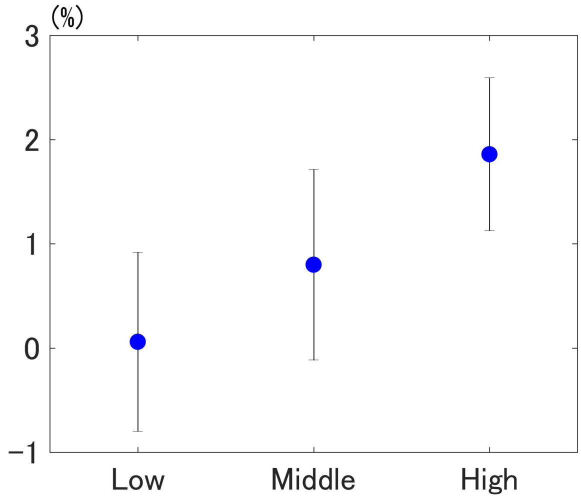
Note: This figure shows the housing tenure for households by income group. "Others" includes households who live in student housing or occupy housing without payment of cash rent. The data come from the CEX.

Figure 2: Income source



Note: This figure shows the source of income of each income group. "Transfer payments" includes unemployment insurance, social security and pension payments, welfare, worker's compensation and other transfer program benefits. "Others" includes financial income and business income. The data come from the CEX.

Figure 3: Cumulative consumption response by income group



Note: This figure shows the cumulative consumption response by each income group over ten quarters after an expansionary monetary policy shock. The magnitude of the monetary policy shock is normalized so that the federal funds rate decreases by 0.25%. The error bars indicate 90% confidence intervals. Low, middle, and high income households correspond to households in the lowest 1/3, middle 1/3, and the highest 1/3 of the annual income before tax, respectively.

3.2 Consumption response to monetary policy shocks

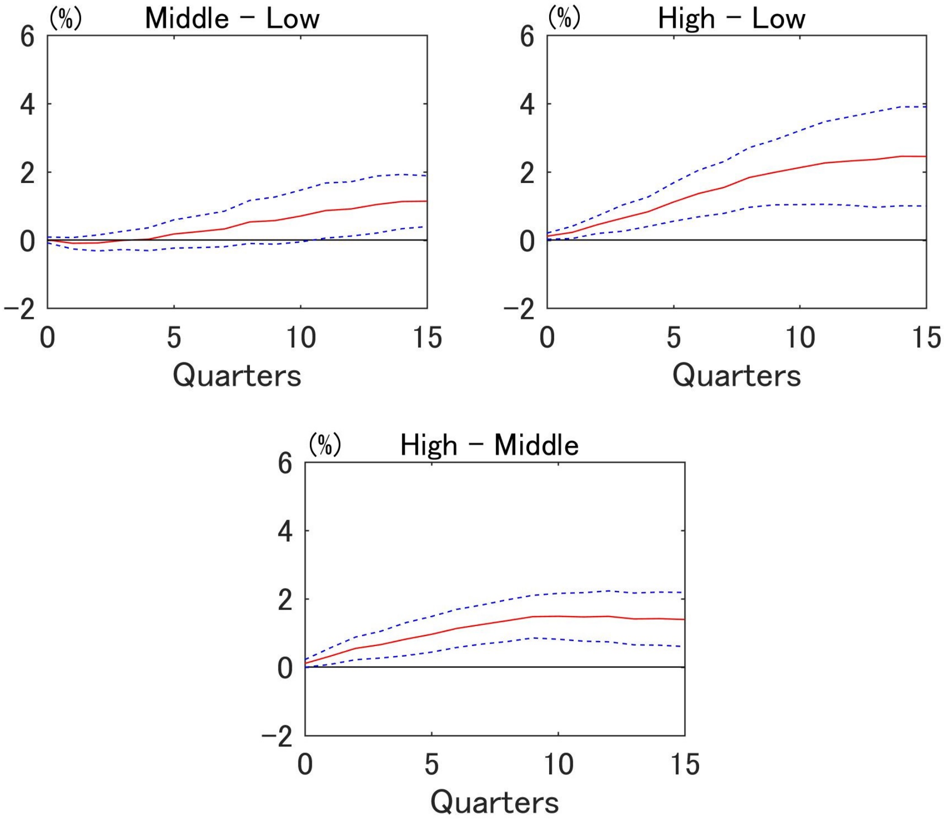
Consumption response by income group

Figure 3 shows the cumulative consumption response for each income group over ten quarters after an expansionary monetary policy shock. The magnitude of the monetary policy shock is normalized so that it causes a decrease in the federal funds rate of 0.25%. From Figure 3, we can see that the response of high income households is larger than that of middle and low income households. Moreover, the point estimate of high income households' cumulative consumption response is approximately 2 percentage points larger than that of low income households.[25]

Furthermore, we check whether these differences in consumption responses are statistically significantly different from zero. Figure 4 shows the differences in consumption responses to an expansionary monetary policy shock. While the consumption response for middle income households is not statistically significantly

[25]We check the validity of the response obtained by comparing these results with the results using aggregate variables. The magnitude of the cumulative consumption response over ten quarters after an expansionary monetary policy shock is 1.0 when using all the CEX data. This result is in line with the consumption response of 1.2 obtained when using the aggregate consumption series from the NIPA as the dependent variable in the empirical specification shown in equation (1). Moreover, the magnitude of the consumption response estimated is within the range of that documented in studies such as Christiano et al. (1996) and Wu and Xia (2016), which are based on aggregate output data.

Figure 4: Differences in consumption responses



Note: This figure shows the differences in consumption responses to an expansionary monetary policy shock. The magnitude of the monetary policy shock is normalized so that the federal funds rate decreases by 0.25%. The dashed lines indicate 90% confidence intervals. The top-left, top-right and bottom panels show the difference in consumption responses for middle income households relative to low income households, high income households relative to low income households, and high income households relative to middle income households, respectively.

different from that of low income households in the first ten quarters, we can see that the responses of high income households compared to both low and middle income households are statistically significantly different during the entire period.[26] In summary, the consumption response of high income households is significantly larger than that of middle and low income households.

As discussed above, the standard Aiyagari-Bewley-Huggett model cannot explain the larger consumption response of high income households compared to that of lower income households. We therefore relax the two assumptions made in the standard model - namely that both the income composition across households and the degree of liquidity of assets held by households are homogenous - so that the

[26]Appendix C provides robustness checks of these results.

model can capture the empirical features of section 3.1 and study its implications.

Potential channel: illiquid assets

Figure 1 of the previous section shows that high income households tend to own their homes. Home ownership can increase the consumption response of high income households in two ways. Firstly, housing can be considered to be an illiquid asset because the purchasing and selling of housing involves transaction costs.[27] Through purchasing illiquid assets, high income households, who can afford to pay the transaction costs, choose to hold little or no liquid assets and exhibit a high MPC out of additional transitory income. This is because they are better off if they receive the higher capital income generated from illiquid assets rather than if they smooth their consumption through holding low return liquid assets. Secondly, it is well-known that the real value of housing wealth increases in response to an expansionary monetary policy shock and that such an increase in wealth translates into a rise in consumption.[28]

Potential channel: heterogeneous transfer payments

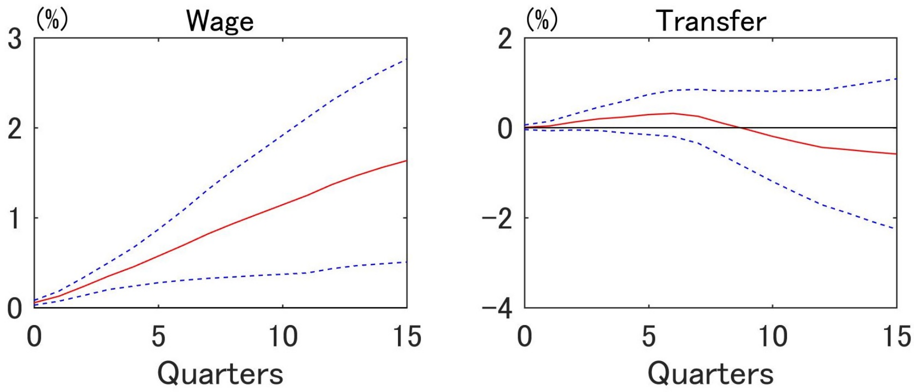
Figure 2 in section 3.1 shows that the main source of income for high income households is their labor earnings, while for low income households it is transfer payments. Due to this heterogeneity in the share of transfer payments in income, the size of the increase in income followed by an expansionary monetary policy shock can differ across income groups given the fact that the response of labor earnings to a monetary policy shock is different from that of transfer payments. Figure 5 shows the cumulative impulse responses to an expansionary monetary policy shock of real wages (left) and real transfer payments (right) by estimating equation (1) using the log of real wages and the log of real transfer payments for each income group as the dependent variable instead of the log of consumption, y^i_{t+h}. One can see that an expansionary monetary policy shock has a statistically significantly positive impact on real wages, while the response of transfer payments has large standard errors and is not statistically significant from zero.[29] As a result, the income response of high income households to an expansionary shock is large. On the other hand, the main income source of low income households is transfer payments, the size of which is independent of monetary policy shocks. Because changes in income are easily

[27]We focus mainly on the illiquidity of housing as an asset. Purchasing a home induces the households' mortgage loan, and its interest rate burden is affected by monetary policy shocks. This aspect of transmission channel is discussed in Wong (2016).

[28]Regarding the relationship between monetary policy shocks, house prices and consumption, Cloyne et al. (2018) show that an expansionary monetary policy shock raises house prices and Guren et al. (2018) argue that household consumption is responsive to changes in house prices.

[29]The estimated responses of real transfer payments and real wages are in line with those found in Cloyne et al. (2018) and Forni and Gambetti (2010), respectively.

Figure 5: Cumulative wage and transfer payment responses



Note: This figure shows the cumulative impulse responses to an expansionary monetary policy shock of real wages (left) and real transfer payments (right). The magnitude of the monetary policy shock is normalized so that the federal funds rate decreases by 0.25%. The dashed lines indicate 90% confidence intervals.

translated to changes in consumption, this difference in income responses across households is one potential explanation for why the consumption response of high income households is larger than that of low income households.[30]

4 The model

In this section, we build a model to account for the key empirical findings of the previous section. The key features of the model are idiosyncratic productivity shocks, heterogeneous transfer payments and illiquid assets. The model is based on Kaplan et al. (2018). However, there are two differences. Firstly, we incorporate heterogeneous transfer payments into the model. Secondly, whereas Kaplan et al. (2018) use a general equilibrium framework, we focus on households' decision problem for simplicity.[31]

[30] One might wonder whether we can quantify the two channels that arise from income heterogeneity and the holding of illiquid assets by further dividing households by income source and housing tenure and estimating the consumption response using the local projection method. Unfortunately, the results of such an exercise are not statistically significant because of the small sample size. We therefore use a model to quantify the importance of these channels.

[31] Wong (2016) also focuses on the households decision problem when quantifying the importance of the transmission channel of monetary policy.

4.1 Households

A continuum of households is indexed by their holdings of liquid assets b, illiquid assets a, and their labor productivity z.[32] As we use continuous time, the joint distribution of households can be described at each instant time in t as $\mu_t(da, db, dz)$. Labor productivity is idiosyncratic, uninsurable and follows an exogenous Markov process that we describe in detail in section 4.4.

Liquid assets

Households can save or borrow liquid assets b without transaction costs. Liquid asset borrowings must be above the exogenous limit $-\underline{b}$. We assume that there exists an exogenous wedge $\kappa > 0$ between the interest rate on borrowings r_t^{b-} and the interest rate on savings r_t^{b+} described as

$$r_t^{b-} = r_t^{b+} + \kappa. \tag{3}$$

Thus, the interest rate on liquid assets is r_t^{b+} when $b_t > 0$, and r_t^{b-} when $b_t < 0$. We use $r_t^b(b_t)$ for the interest rate on liquid assets to simplify this expression.

Illiquid assets

The essential characteristics of illiquid assets a are that their rate of return r_t^a is higher than that of liquid assets, r_t^b, but require households to pay transaction costs. The functional form of transaction costs $\chi(d, a)$ is the same as that in Kaplan et al. (2018), and is given by

$$\chi(d, a) = \chi_0 |d| + \chi_1 \left| \frac{d}{a} \right|^{\chi_2} a, \tag{4}$$

where d is the household's investment in illiquid assets. We assume that $\chi_0 > 0$, $\chi_1 > 0$, and $\chi_2 > 1$. The first term (the kinked cost component) implies that there exists a region of inaction in the household's optimal investment decision. The second term (the convex component) prevents households from investing an infinite amount at one time, so that their holdings of assets never jump.[33] Finally, illiquid asset positions can not be negative.

Preferences

Households' utility comes from their consumption $c_t \geq 0$ with discount rate $\rho \geq 0$. Formally, households maximize their utility, described as

[32]We omit subscript of each individual i to ease the notation.

[33]The transaction costs at $a = 0$ are infinite when we use this form. To avoid this, we replace a in equation (4) with $\max(a, \underline{a})$, where $\underline{a}$ is the minimum threshold value.

$$\mathbb{E}_0 \int_0^\infty e^{-\rho t} u(c_t) dt, \tag{5}$$

where $\mathbb{E}_0$ is the expectation operator at time 0, taken over the realizations of idiosyncratic productivity shocks. We assume that households have a CRRA instantaneous utility function,

$$u(c) = \frac{c^{1-\gamma}}{1-\gamma}, \tag{6}$$

where $\frac{1}{\gamma}$ is the intertemporal elasticity of substitution.[34]

Dynamics of assets holdings

Households' asset holdings evolve according to

$$\dot{b}_t = (1-\tau_t) z_t w_t + r_t^b(b_t) b_t - c_t - d_t - \chi(d_t, a_t) + T_t(z_t w_t), \tag{7}$$

$$\dot{a}_t = r_t^a a_t + d_t, \tag{8}$$

where $\dot{b}_t$ is the household's savings in liquid assets, τ_t is the income tax rate, z_t is the household's labor productivity, w_t is the wage rate,[35] b_t is the household's liquid asset holdings, $r_t^b(b_t)$ is the interest rate on liquid assets, c_t is consumption, d_t is the household's investment in illiquid assets, $\chi(d_t, a_t)$ represents the transaction costs, and T_t is government transfer. We assume that government transfers $T_t(z_t w_t)$ depends on the household's labor earnings, which results in heterogeneous transfer payments.

Equation (7) implies that the savings (or borrowings) of liquid assets $\dot{b}_t$ are equal to the household's income (composed of labor earnings, the return on liquid assets and transfer payments) net of expenditure (composed of consumption, investment in illiquid assets and transaction costs). Equation (8) implies that the net savings of illiquid assets $\dot{a}_t$ are equal to the sum of investment in illiquid assets and the return on illiquid asset holdings.

4.2 HJB and Kolmogorov forward equations

For the household's problem we can write down the Hamilton-Jacobi-Bellman (HJB) equation and Kolmogorov forward equation. The household's consumption-savings decision and the evolution of the joint distribution of households can be summarized with these two partial differential equations. For simplicity, we provide only the stationary version of these equations. Achdou et al. (2017) describe in detail how to derive and solve the dynamic versions of these equations.

[34] We assume $\gamma \geq 0$.

[35] Real labor earnings of each household are given by $z_t w_t$.

The HJB equation is given by

$$\begin{aligned}\rho V(a,b,z) &= \max_{c,d} u(c) + V_b(a,b,z)[(1-\tau)zw + r^b(b)b - c - d - \chi(d,a) + T(zw)] \\ &+ V_a(a,b,z)(r^a a + d) + \sum_{z'} \lambda(z,z')(V(a,b,z') - V(a,b,z)), \end{aligned} \quad (9)$$

where $V(a,b,z)$ is the value function of a household with illiquid assets a, liquid assets b and labor productivity z. $V_b(a,b,z)$ and $V_a(a,b,z)$ are the derivatives of the value function with respect to b and a, respectively. Households switch from state z to z' according to a Poisson process with arrival rate $\lambda(z,z')$.[36] This equation provides the household's optimal decision of consumption and savings.

The Kolmogorov forward equation is given by

$$\begin{aligned} 0 &= -\partial_a(s^a(a,b,z)g(a,b,z)) - \partial_b(s^b(a,b,z)g(a,b,z)) \\ &+ \sum_{z' \neq z} \left[-\lambda(z,z')g(a,b,z) + \lambda(z',z)g(a,b,z')\right], \end{aligned} \quad (10)$$

where $g(a,b,z)$ is a stationary density function.[37] $s^a(a,b,z)$ and $s^b(a,b,z)$ denote the optimal illiquid and liquid asset savings policy functions, which determin the amount of savings in illiquid and liquid assets when households select the choice variables optimally. The Kolmogorov forward equation provides the household's joint distribution of liquid assets, illiquid assets and labor productivity.

4.3 Definition of impulse response function

In order to estimate the response of consumption to a monetary policy shock, we study the percentage change in consumption under an expansionary monetary policy shock $\tilde{\epsilon}_0 < 0$ relative to that in the steady state. This expansionary shock, which is unexpected to households, induces deterministic changes in wages and interest rates. In the period when the shock occurs, households are informed of the dynamics of wages and interest rates from $t = 0$ to ∞, and exploit this information when making their decisions.

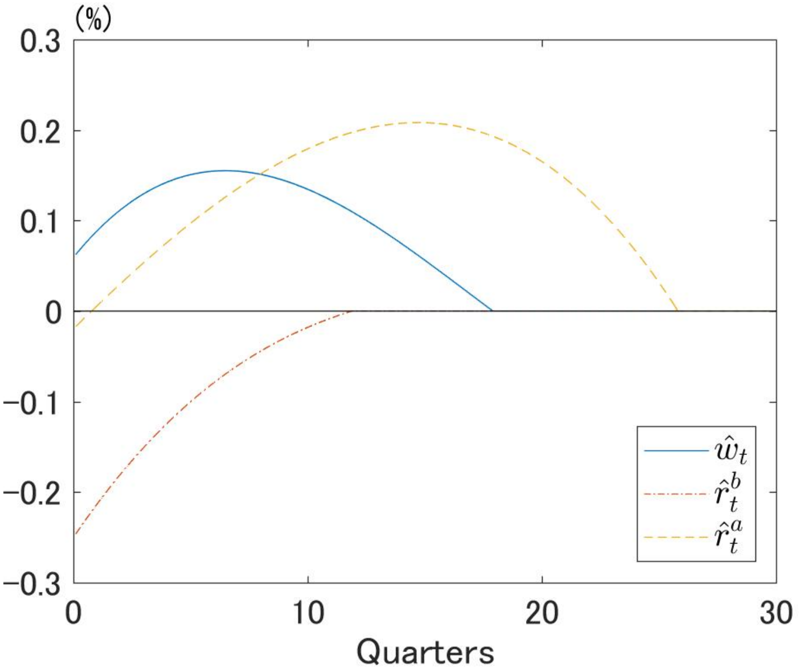
Formally, the k-period ahead impulse response function of consumption can be described by

$$IRF(k) = \ln C_k(\{\Gamma_{t'}\}_{t' \geq 0} | \epsilon_{t=0} = \tilde{\epsilon}_0) - \ln C_k(\{\Gamma_{t'}\}_{t' \geq 0} | \epsilon_{t=0} = 0). \quad (11)$$

[36]Note that the last term of equation (9) does not include the derivative with respect to z, since z is discrete variable.

[37]Note that $\mu(a,b,z)$ is the stationary distribution of households and $g(a,b,z)$ is the corresponding density function.

Figure 6: Wage and interest rate deviations from steady state



Note: This figure shows wage and interest rate deviations from their steady state values following an expansionary monetary policy shock at $t = 0$. These response functions are empirically estimated separately using the local projection method. $\hat{w}_t$, $\hat{r}_t^b$ and $\hat{r}_t^a$ represent the wage rate, interest rate on liquid asset, and interest rate on illiquid asset deviations. We normalize the monetary policy shock so that it decreases r_t^b by 0.25%.

Here, Γ_t represents the interest rate on illiquid assets, the interest rate on liquid assets and the wage rate $\{r_t^a, r_t^b, w_t\}$.[38] C_t denotes aggregate consumption at time t, which is described by

$$C_t\left(\{\Gamma_{t'}\}_{t'\geq 0}\right) = \int c_t\left(a, b, z; \{\Gamma_{t'}\}_{t'\geq 0}\right) d\mu_t. \tag{12}$$

$\mu_t(da, db, dz; \{\Gamma_{t'}\}_{t'\geq 0})$ is the household's joint distribution of liquid assets, illiquid assets and productivity. $c_t\left(a, b, z; \{\Gamma_{t'}\}_{t'\geq 0}\right)$ is the household's consumption policy function. Since households are forward looking, their consumption decision depends on the vector of future interest rates and wages $\{\Gamma_{t'}\}_{t'\geq 0}$.

In this exercise, we set $\{\Gamma_t\}$ exogenously so that its values are consistent with those empirically estimated using the local projection method described in section 2. Using this exogenous $\{\Gamma_t\}$ simplifies the interpretation of the simulation results. What we need for the estimation of the consumption response is wage and interest

[38]The dynamics of taxes and transfer payments used in this exercise are described in detail in section 4.4.

rate deviations from their steady state values. For the deviation of wages $\hat{w}_t$, and the deviation of the interest rate on liquid assets $\hat{r}_t^b$, we use the impulse responses of real wages and the federal funds rate. For the deviation of the rate of return on illiquid assets $\hat{r}_t^a$, we use the impulse response of the Case-Shiller home price index.[39] The dynamics of the deviations of wages and interest rates from their steady state values following an expansionary monetary policy shock at $t = 0$ are described in Figure 6. We normalize the monetary policy shock so that r_t^b decreases by 0.25%, which is consistent with the empirical analysis above.[40] The results are within the range of estimates found in studies such as Coibion et al. (2017).[41] Note that the empirical analysis provides us with impulse responses only on a quarterly basis, while the simulation requires responses of wages and interest rates at a higher frequency. To achieve this, we smooth and interpolate the quarterly dynamics of wages and interest rates.

4.4 Parametrization

Firstly, we set the value of income variables to be consistent with the CEX data used in the empirical analysis, as briefly described in Table 1. We discretize productivity z into three states following the empirical analysis: low z_1, middle z_2, and high z_3. The first row of Table 1 shows the median income before tax of each income group.[42] The second row shows labor earnings as a percentage of the sum of labor earnings and transfer payments, taken from Figure 2.[43] We calibrate productivity, shown in the third row, so that the household labor earnings of each income group matches the values calculated in the first and second rows of the table. The values are normalized so that the average productivity of all agents is unity.

For the transition matrix of the productivity process P, we assume the following form,

[39] Kaplan, Violante, and Weidner (2014) show that 56% of illiquid assets are housing, which is consistent with the SCF data analysis shown in appendix B. Other illiquid assets include retirement accounts and life insurance, which do not necessarily respond positively to an expansionary monetary policy shock. Thus, we multiply the Case-Shiller housing wealth return by 56% to match the data. Other illiquid asset return cases are considered in appendix D.

[40] We use the federal funds rate for estimating the response of liquid assets to monetary policy shocks. Thus, the magnitude of the monetary policy shock in the simulation is adjusted to match the empirical analysis.

[41] Note that in Figure 5, the response of wages is shown cumulatively, but in Figure 6 it is not.

[42] The data come from the CEX. The sample period is 1980Q1 to 2008Q4.

[43] We omit the "others" category in Figure 2 for simplicity.

Table 1: Calibration for income

	Low	Middle	High
Median income before tax (2016 dollars)	14,000	46,000	107,000
Labor earnings/(Labor earnings + Transfer payments)	49%	84%	97%
Normalized productivity	0.14	0.78	2.08

Note: The data of the first and second rows come from the CEX. The calibrated productivity is calculated from these values and shown in the third row. The productivity values are normalized so that the average productivity of all agents is unity. Details are provided in the text.

$$P = \begin{pmatrix} 1-\lambda & \lambda & 0 \\ \lambda & 1-2\lambda & \lambda \\ 0 & \lambda & 1-\lambda \end{pmatrix}. \tag{13}$$

This form implies that households are distributed equally (the fractions of households in each income group are the same) and that the transition process is symmetric. Moreover, we assume that no low income household becomes a high income household without first becoming a middle income household and vice versa. We use $\lambda = 0.021$ in the simulation to match the AR(1) coefficient on wages from Floden and Lindé (2001)'s empirical study of wage persistence.

The size of transfer payments is set so that the ratio of labor earnings to the sum of labor earnings and transfer payments matches the values shown in Table 1.[44] The tax rate τ is set so that the government budget balances in each time period.[45]

The remaining parameter values are set following Kaplan et al. (2018), as shown in Table 2. We set the intertemporal elasticity of substitution of households $1/\gamma$ to 1. The annual discount rate ρ is set to 6%, the wage rate w to 1, and the borrowing limit on liquid assets to $-4z_1w$, which is equal to the annual income of low income households. We set the annual steady-state return on savings to liquid assets $\bar{r}_b^+$ to 2%, and the wedge between the interest rate on borrowings of liquid assets and savings of liquid assets κ to 5%, which implies that steady-state interest rate on

[44] The specific value of transfer payments is $T_1 = 0.14w$ for low income households, $T_2 = 0.15w$ for middle income households, and $T_3 = 0.07w$ for high income households.

[45] There are three ways to adjust transfers and taxes so that the government budget balances even when there are monetary policy shocks. The first is to fix the size of the transfer and change the tax rate to balance the budget. The second is to keep the tax rate fixed and adjust transfers to balance the budget. The third is to keep both the tax rate and the size of transfers fixed so that fiscal policy is independent from monetary policy. In the last case, we set $\tau = 0$, and allow the government to collect taxes in proportion to households' earnings. We use the third case in the baseline simulation. All three cases give similar results.

Table 2: Parameter values

Parameter	Explanation	Value
$1/\gamma$	Intertemporal elasticity of substitution	1
ρ	Discount rate (annual)	0.06
w	Wage rate	1
$\underline{b}$	Borrowing constraint	-0.56
$\bar{r}_b^+$	Interest rate on liquid asset savings (annual)	0.02
$\bar{r}_b^-$	Interest rate on liquid asset borrowings (annual)	0.07
$\bar{r}_a$	Rate of return on illiquid assets (annual)	0.05
χ_0	Adjustment cost	0.25
χ_1	Adjustment cost	1.99
χ_2	Adjustment cost	2

borrowings of liquid assets $\bar{r}_b^-$ is 7%. Given these parameter values, we set the annual steady-state return on illiquid assets $\bar{r}_a$ to 5% so that the aggregate amount of illiquid assets is 2.9 times household earnings.[46] With regard to adjustment costs, we set $\chi_2 = 2$, which imples a quadratic convex component. Our target for the coefficients on the linear and convex components are the ratio of liquidity constrained households to entire households. We thus set $\chi_0 = 0.25$ and $\chi_1 = 1.99$ to match the propotion of "poor hand-to-mouth" households as 0.12 and "wealthy hand-to-mouth" as 0.13.[47]

5 Computational experiments

In this section, we describe the quantitative simulation results based on the model.

5.1 Heterogeneous consumption response to monetary policy shocks

Firstly, we compare the consumption response obtained from the empirical analysis with the response obtained from the model simulation. Figure 7 shows the difference

[46] We allow for the rate of return on illiquid assets to be slightly lower when households have large holdings, which prevents them from accumulating infinite amounts of illiquid assets. This can be interpreted as a maintenance cost, which reduces the return on large holdings of illiquid assets.

[47] These ratios are taken from Kaplan, Violante and Weidner (2014). "Poor hand-to-mouth" households and "wealthy hand-to-mouth" households correspond to households with "$b <= 0, a = 0$" and "$b <= 0, a > 0$" in the model. The model gives us aggregate transaction costs of 4% of households' earnings, which is similar to the value in Kaplan et al. (2018). We try other values for the adjustment costs and find that the model provides similar results as long as the adjustment costs are low enough so that households accumulate illiquid assets.

in consumption response to an expansionary monetary policy shock between the empirical analysis and the model. The top-left, top-right and bottom panels show the difference in consumption responses for middle income households relative to low income households, high income households relative to low income households and high income households relative to middle income households, respectively. The empirical results are taken from Figure 4 and the dashed lines indicate 90% confidence intervals. One can observe that the simulation results from the model with illiquid assets and heterogeneous transfer payments are consistent with the empirical analysis. The simulation results fall within the 90% confidence intervals of the empirical analysis. In particular, the shape of the difference in consumption response for high income households compared to low income households generated from the model simulation is almost the same as that from the empirical analysis.

5.2 The role of illiquid assets and heterogeneous transfer payments

Shutting down experiments

How important are the illiquid asset and heterogeneous transfer payments channels for explaining the empirical results? To answer this question, we shut down the channels in the model and repeat the simulation.

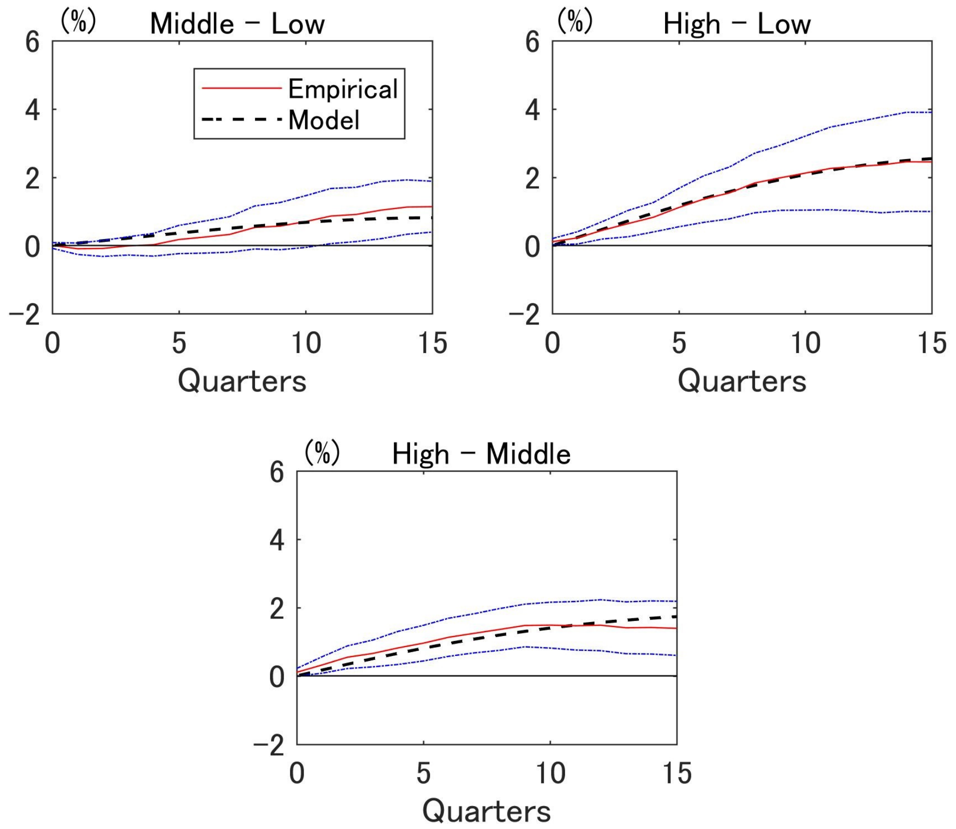
Figure 8 compares the cumulative consumption response over ten quarters after an expansionary monetary policy shock under various assumptions. Two findings are notable.[48] Firstly, incorporating illiquid assets is crucial to explain the empirical results. Comparing the top-left and top-right panels in Figure 8, one can see that by incorporating illiquid assets, the consumption response of high income households relative to low income households becomes positive and falls within the error bars of the empirical analysis. Secondly, a comparison between the top-left and bottom-left panels shows that incorporating heterogeneous transfer payments contributes to making the high income households' response larger relative to that of the low income households, although the effect is quantitatively limited.

Intuition behind the model

The key features of illiquid assets are that they require transaction costs, but they yield a higher rate of return. Including illiquid assets in the model contributes to an increase in the consumption response of high income households to an expansionary monetary policy shock in two ways. Firstly, high income households invest their liquid savings in illiquid assets so that they can earn a higher return than

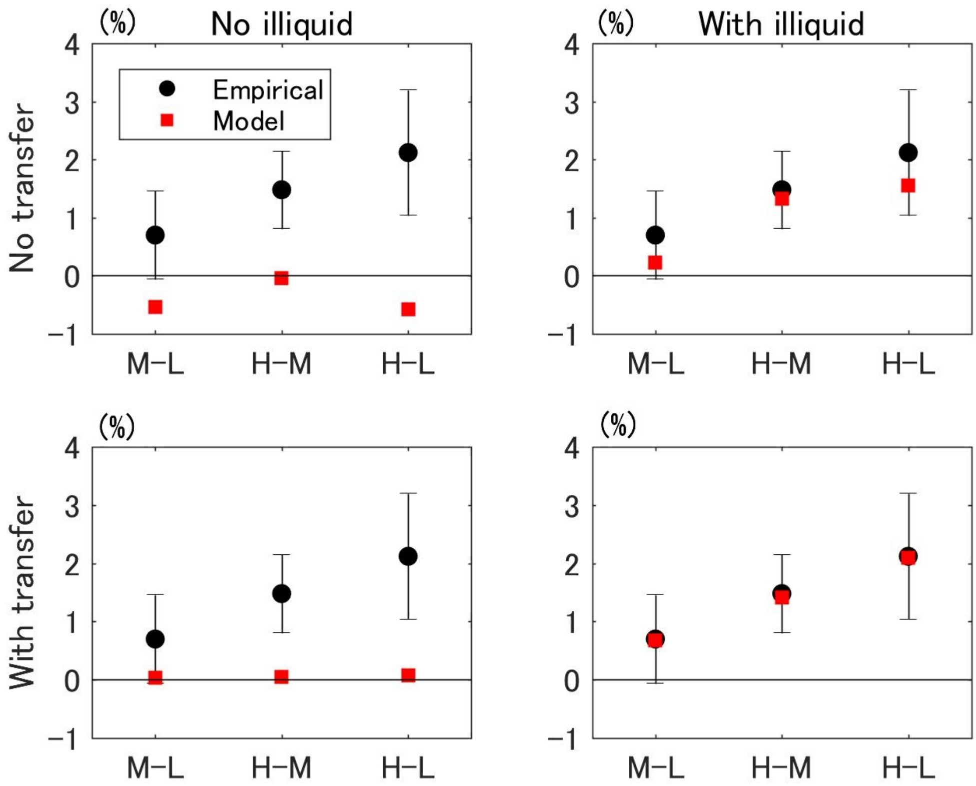
[48]In the top-left panel, low income households exhibit the largest response to an expansionary monetary policy shock, which is consistent with the implications of the Aiyagari-Bewley-Huggett model.

Figure 7: Comparison of difference in consumption response



Note: This figure shows the difference in consumption responses to an expansionary monetary policy shock. The top-left, top-right and bottom panels show the difference in consumption responses for middle income households relative to low income households, high income households relative to low income households, and high income households relative to middle income households, respectively. The magnitude of the monetary policy shock is adjusted to match the empirical analysis as described in section 4.3.

Figure 8: Comparison of consumption response under various assumptions



Note: This figure shows the cumulative consumption response over ten quarters after an expansionary monetary policy shock under various assumptions. The left-hand-side, middle, and right-hand-side plots in each panel show the difference in consumption responses for middle income households relative to low income households, high income households relative to middle income households, and high income households relative to low income households, respectively. The error bars indicate the 90% confidence intervals taken from the empirical analysis. The top-left panel corresponds to the case without illiquid assets or heterogeneous transfers (i.e. the standard Aiyagari-Bewley-Huggett model). The top-right panel corresponds to the case with illiquid assets but without heterogeneous transfers. The bottom-left panel corresponds to the case with heterogeneous transfers but without illiquid assets. Finally, the bottom-right panel corresponds to the baseline model (with both illiquid assets and heterogeneous transfers).

from holding low-return liquid assets. Thus, the addition of illiquid assets into the model allows high income households to exhibit a higher MPC because they face liquidity constraints. This contrasts with the standard Aiyagari-Bewley-Huggett model, where only low income households exhibit a high MPC due to borrowing constraints. Secondly, it is well-known that the value of illiquid assets increase more in response to expansionary monetary policy shocks than the value of liquid assets. Since high income households tend to hold more illiquid assets, their lifetime income becomes greater after expansionary monetary policy shocks, which in turn increases their consumption.

The heterogeneous transfer payments channel operates through the following mechanism. Transfer payments, which are independent from monetary policy shocks, account for a large percentage of the income of low income households. On the other hand, the main income source of high income households is labor earnings, which increases after expansionary monetary policy shocks. Thus, the percentage increase in income of high income households in response to an expansionary shock is larger than that of low income households. All else equal, this makes the consumption response of high income households larger than that of low income households. However, based on our simulation, the contribution of this channel is quantitatively limited. That might be because although holding illiquid assets makes the MPC of high income households higher and increases their lifetime income by more, heterogeneous transfer payments affect only differences in households' lifetime income, leaving their MPCs unchanged.

6 Conclusion

In this paper, we address the questions of which income category of households is the most responsive to monetary policy shocks and why. Using CEX data and monetary policy shocks extracted following the approach of Romer and Romer (2004), this paper empirically shows that the consumption response of high income households to an expansionary monetary policy shock is larger than that of low income households. Moreover, empirical facts suggest that the composition of income source and housing tenure are different between high income households and low income households. Motivated by these empirical findings, we incorporate illiquid assets and heterogeneous transfer payments into an otherwise standard Aiyagari-Bewley-Huggett model to quantify the importance of these transmission channels. We find that incorporating illiquid assets is key to explain the empirical result that high income households' consumption response is larger than that of low income households. This is because illiquid assets increase the MPC of high income households and provide them with a higher rate of return.

There are two caveats to our analysis. Firstly, other channels can potentially contribute to the higher cyclicality of the consumption response of high income households. Studies such as Coibion et al. (2017) and Inui et al. (2017) point out two other channels: the wage heterogeneity channel, and the portfolio channel. The wage heterogeneity channel arises when the response of wages to a monetary policy shocks is different across households depending on their productivity or industry in which they work. In contrast, we assume a homogeneous wage response to monetary policy shocks across all households. Nakajima (2015) suggests that accommodative monetary policy can reduce low income households' risk of unemployment.[49] As a result, low income households might experience larger increases in income from an expansionary shock through the wage heterogeneity channel. Thus, incorporating this channel will lower the consumption response of high income households relative to low income households, which is in contrast to our empirical results. However, incorporating this channel into the model is likely to play only a limited role in the simulation results.[50] The portfolio channel matters when the asset holdings differ across households. We include illiquid assets as well as liquid assets, but we do not consider financial assets such as equity.[51] The effects of this channel can be limited in our empirical analysis, since the rate of return on equity investments is especially important for exceptionally wealthy households, such as the top 1%, as described in Diaz-Gimenez et al. (2011).

Secondly, this paper does not include an analysis of unconventional monetary policy. This is because it remains challenging to empirically identify the exogenous component of unconventional monetary policy shocks. In addition, although our model considers only conventional monetary policy, we could include forward guidance as well as large scale asset purchases following McKay et al. (2016) and Del Negro et al. (2017). Developing the model in this direction is left for future research.

[49] Empirically, Elsby et al. (2010) point out that monetary policy can be more effective for the wages of low income households.

[50] Simulations suggest that the heterogeneous transfer payments channel plays a limited role compared to the illiquid assets channel. This might be because while illiquid asset holdings make the MPC of high income households higher and increase their lifetime incomes by more, heterogeneous transfer payments affect only differences in households' lifetime incomes, leaving their MPCs unchanged. This suggests that the contribution of the wage heterogeneity channel, which leaves the MPC unchanged, should be limited.

[51] For example, if high income households tend to hold more equity, whose rate of return rises in response to expansionary monetary policy shocks by more, then incorporating the portfolio channel into the model would raise the consumption response of high income households relative to low income households.

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A Construction of consumption data by income group

A.1 Details of CEX data

The CEX contains the statistics of what the U.S. households consume. The CEX consists of two different surveys with different questionnaires and samples: a quarterly Interview Survey and a weekly Diary Survey. This paper uses only the data from the Interview Survey.[52] In the survey, each household is interviewed every three months over four consecutive quarters. Each quarter, part of the sample is replaced, which means that the resulting data form a rotating panel. The CEX dataset is provided by the Bureau of Labor Statistics (BLS) and the Inter-university Consortium for Political and Social Research (ICPSR) at the University of Michigan.

A.2 Data cleaning

We restrict the sample used in the regression analysis to ensure that the data are comparable over time, as in Coibion et al. (2017), Aguiar and Hurst (2013) and others. We eliminate observations that report zero expenditure on food, which we define as the sum of food at home and food away from home, in any interview. Furthermore, we drop all households that report negative expenditures in any category which should not be negative, such as elderly care. We winsorize income and spending variables at top and bottom 1 percent so that we can reduce the influence of outliers.

A.3 Income imputation

The BLS began to impute income beginning in 2004. For the data prior to 2004, we follow Fisher, Johnson and Smeeding (2013) in imputing income. Specifically, for households who refuse to provide their exact income but provide their income range in the questionnaire, we use the mid-point of the bracket selected. For the remaining households, we regress income on age, age squared, income reporting date, gender, race, education, number of weeks worked full or part time in the last 12 months, family size, number of children, number of persons over 64, and number of earners. We use sampling weights for all regressions. To make the sampling random, we add residuals drawn from a random number generator.

[52]The Interview Survey includes a larger coverage of expenditure than the Diary Survey. On the other hand, the Diary Survey focuses on goods related to food and housekeeping supplies with detailed categories. We use the Interview Survey so that we can focus on the broader elements of household consumption.

A.4 Consumption data construction

Household consumption is defined as the sum of non-durables expenditure, services expenditure and expenditures on durable goods, following Coibion et al. (2017), Krueger and Perri (2006) and others. We correct sample breaks caused by changes in the questionnaire.[53] All nominal variables are deflated using the CPI-U. To adjust for differences in household size, we divide consumption by the OECD scale, which is the effective number of household members.[54]

A.5 Limitations of data

Krueger et al. (2010), Aguiar and Bils (2015) and Attanasio et al. (2012) point out that the CEX underreports consumption relative to aggregate data and that this discrepancy becomes larger over time. The discrepancy arises from differences in scope and methodology. For example, aggregate consumption covers the expenditures of nonprofit institutions, military personnel and others whose expenditures are not covered in the CEX. However, the potential underreporting problem is less of a concern in this study. This is because we focus on the cyclical fluctuation of consumption rather than the level of consumption. Moreover, we detrend the data before performing the regressions. As a robustness check, we follow Cloyne et al. (2018) and rescale consumption for each income group by the ratio of the national statistics series to the consumption series constructed using all households in the CEX and find that results are very similar to those in the baseline analysis.

B Additional household characteristics from SCF

In order to complement the analysis of the CEX, we use the household-level balance sheet data from the Survey of Consumer Finance (SCF) regarding household positions on illiquid assets. This is because illiquid assets are not limited only to housing but also include other assets such as retirement accounts. Table 3 shows the median value (in 2016 dollars) of household holdings of illiquid assets.[55] Illiquid assets include housing net of mortgages and home equity loans, retirement accounts, life insurance policies, CDs, and saving bonds. From Table 3, we can see that the

[53]Specifically, we correct the following items: food at home (1982Q1, 1988Q1), property taxes (1991Q1), personal care services (2001Q2), occupation expenditures (2001Q2), and food away from home (2007Q2).

[54]The OECD scale is calculated as $1+0.7\times(N_a-1)+0.5\times N_c$, where N_a is the number of adults, and N_c is the number of children. Note that head of household is counted as 1, remaining adults are counted as 0.7 and children are counted as 0.5. We also checked the consumption response without using OECD scale and results are very similar.

[55]The data come from the 2001 SCF. Essentially we follow Kaplan and Violante (2014) for the data cleaning procedure and definition of illiquid assets.

Table 3: Household holdings of illiquid assets

	Low	Middle	High
Illiquid assets	19,000	70,000	261,000
Housing (net of mortgages)	2,000	40,000	134,000
Retirement accounts	0	2,000	53,000

Note: The data come from the 2001 Survey of Consumer Finances. The numbers of this table show the median (in 2016 dollars). The definition of illiquid assets follows Kaplan and Violante (2014). Details are provided in the text.

amount of illiquid assets holdings, including retirement accounts and other types of assets, is clearly increasing in household income.

C Additional empirical results

We provide three additional results regarding the difference in consumption responses as robustness checks. Firstly, we add latent factors extracted from a large number of the macroeconomic variables included in equation (1) as control variables in case the response of consumption to monetary policy shocks depends on the macroeconomic environment. We extract three principal components from 97 macroeconomic variables, as in Bernanke et al. (2005) and Wu and Xia (2016) and use them as the latent factors. Figure 9 shows the results, which are very similar to those obtained in the baseline analysis shown in Figure 4.

The second robustness check is to use $y^i_{t+h} - y^i_t$ instead of y^i_{t+h} as the dependent variable in equation (1).[56] Figure 10 shows the results. It shows that the consumption response of high income households is larger than that of low income households and the result is statistically significant during the first ten quarters.

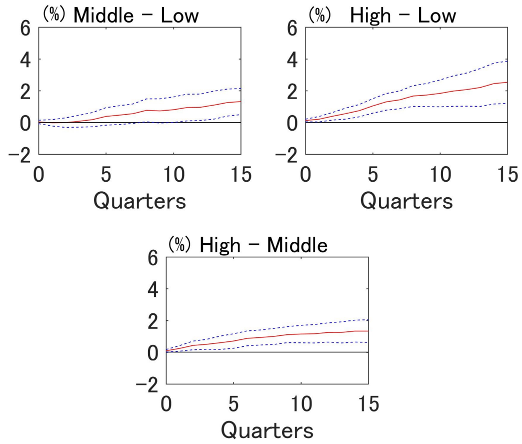
The third robustness check is to exclude the households above age 65. Figure 11 shows the results. It shows that the consumption response of high income households is larger than that of low income households, which is the same as the results obtained in the main text.

D Additional model simulations

We report additional simulation results under alternative scenarios. We check these results because illiquid assets are not limited to housing, but include a variety of

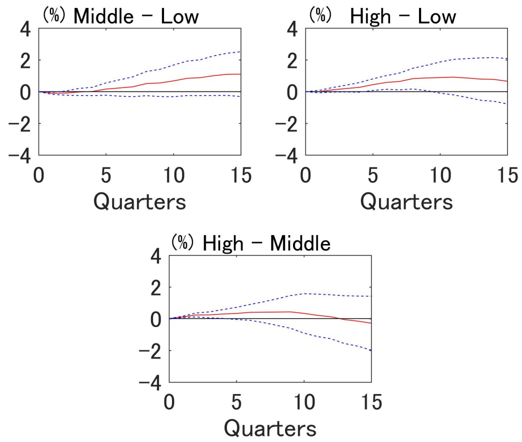
[56] We include this result because related studies, such as Coibion et al. (2017) and Wong (2016), use this differential variable in their analyses. In this case, we do not include a time trend term in the regression.

Figure 9: Difference in consumption responses with three macroeconomic factors



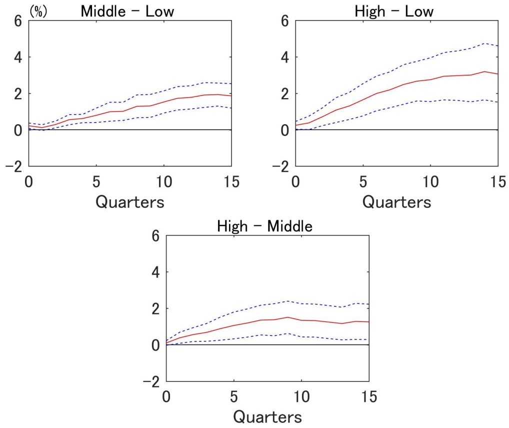
Note: This figure shows the difference in consumption response to an expansionary monetary policy shock when we include three macroeconomic factors as control variables. The magnitude of the monetary policy shock is normalized so that the federal funds rate decreases by 0.25%. The dashed lines indicate 90% confidence intervals. The top-left, top-right and bottom panels show the difference in consumption responses for middle income households relative to low income households, high income households relative to low income households, and high income households relative to middle income households, respectively. See the text for details.

Figure 10: Difference in consumption responses using alternative dependent variable



Note: This figure shows the difference in consumption responses to an expansionary monetary policy shock using the h-period ahead difference dependent variable. The magnitude of the monetary policy shock is normalized so that the federal funds rate decreases by 0.25%. The top-left, top-right and bottom panels show the difference in consumption response for middle income households relative to low income households, high income households relative to low income households, and high income households relative to middle income households, respectively. See the text for details.

Figure 11: Difference in consumption responses excluding retired households



Note: This figure shows the difference in consumption responses to an expansionary monetary policy shock excluding the households above age 65. The magnitude of the monetary policy shock is normalized so that the federal funds rate decreases by 0.25%. The top-left, top-right and bottom panels show the difference in consumption response for middle income households relative to low income households, high income households relative to low income households, and high income households relative to middle income households, respectively. See the text for details.

assets.[57]

Figure 12 shows the response functions of the rate of return on illiquid assets following an expansionary monetary policy shock under alternative scenarios.[58] The baseline case is the same as in the main text. In case 2, we use the response of the entire Case-Shiller housing wealth rate of return.[59] This case corresponds to a larger rate of return on illiquid assets. Case 3 corresponds to the case where the rate of return on illiquid assets is fixed.

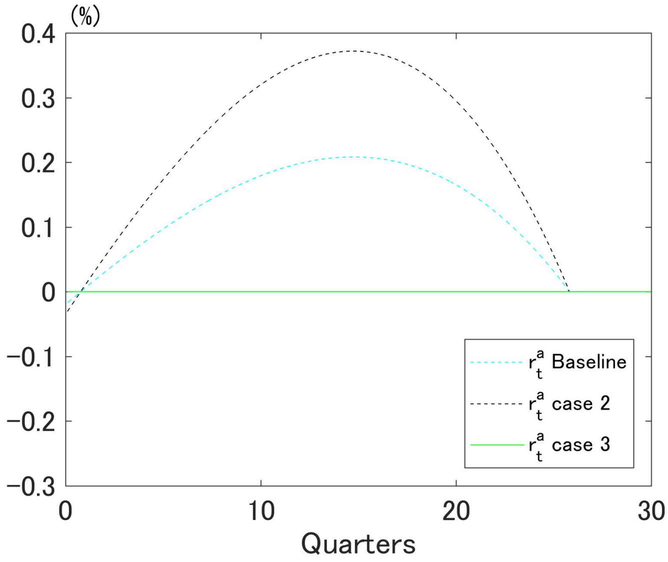
Figure 13 compares the cumulative consumption response over ten quarters after an expansionary monetary policy shock under alternative scenarios. For the model simulation results, we consider the three cases for the rate of return on illiquid assets shown in Figure 12. Figure 13 shows that, in all three cases, the consumption response of high income households is higher than that of low income households, which is consistent with the results obtained in the empirical analysis. Moreover, the difference between the response of high income households and that of low income

[57]For example, Kaplan and Violante (2014) and Kaplan, Violante and Weidner (2014) describe that illiquid assets also include retirement accounts and life insurance.

[58]For the simulation we use the same wage rate and interest rate on liquid asset dynamics as in section 4.3.

[59]In the baseline case, we multiply the response of the Case-Shiller housing wealth return by 56% in order to obtain the rate of return on illiquid assets, following Kaplan, Violante and Weidner (2014).

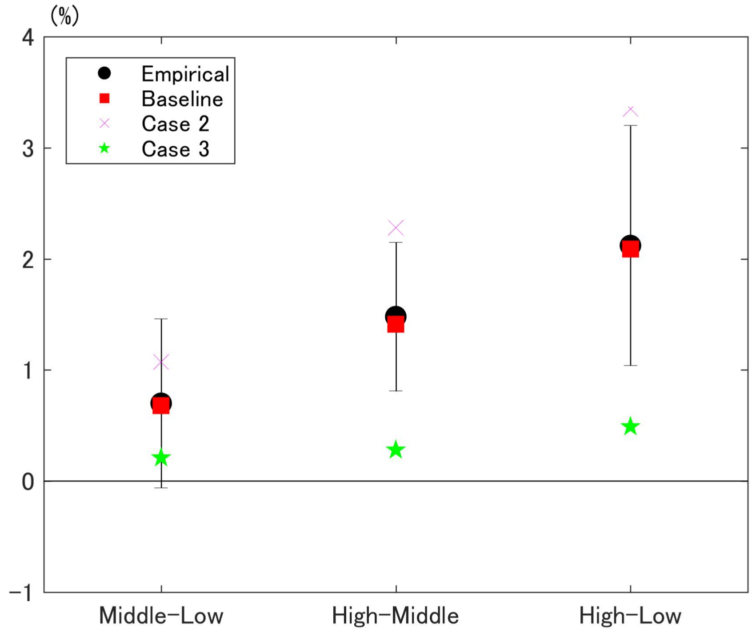
Figure 12: Response functions of the rate of return on illiquid assets under alternative scenarios



Note: This figure shows the response functions of the rate of return on illiquid assets following an expansionary monetary policy shock. We normalize the monetary policy shock so that it decreases the rate of return on liquid assets by 0.25%. Three cases are considered. The baseline case corresponds to the case considered in the main text. Case 2 corresponds to the case where the rate of return on illiquid assets is larger than that in the baseline case. Case 3 corresponds to the case where the rate of return on illiquid assets does not react to shocks. Details are provided in the text.

households is larger when the rate of return on illiquid assets is higher. Thus, the positive response of housing wealth to an expansionary shock can be one reason why the consumption response of high income households is larger than that of low income households.

Figure 13: Comparison of the cumulative consumption response under alternative scenarios



Note: This figure shows the cumulative consumption response over ten quarters after an expansionary monetary policy shock based on the model and the data. The left-hand side, middle and right-hand side plots show the difference in consumption responses for middle income households relative to low income households, high income households relative to middle income households, and high income households relative to low income households, respectively. The error bars indicate the 90% confidence intervals from the empirical analysis. We consider three cases for the response of the interest rate on illiquid assets. See the footnote to Figure 12 for an explanation of the three cases. Details are provided in the text.