

Imperfect Information and Slow Recoveries in the Labor Market

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Abstract

Unemployment rate remains persistently high after recessions even after job losses subside. Standard search and matching models have difficulty capturing this pattern. In this paper, I argue that noise shocks, which capture agents' expectational errors due to the noise in received signals about the persistence of aggregate productivity, can generate substantial persistence in the unemployment rate. I first identify these noise shocks using a novel structural VAR and find that unemployment would have recovered to its pre-recession level 7 quarters earlier in the absence of noise shocks in the 1968-2019 period. Moreover, the importance of these shocks in explaining labor market dynamics increased over time. I then set-up a general equilibrium search and matching model with on-the-job search, endogenous search effort and wage rigidity and consider three shocks: a permanent productivity shock; a transitory productivity shock and a noise shock. Noise shocks capture imperfect information about the underlying persistence of aggregate productivity shocks. The model calibrated to target standard moments and disciplined to match impulse responses identified through SVAR does substantially better compared to a model without imperfect information. It generates 23 percent more volatility in unemployment and vacancies and 6 quarters or 30% longer recoveries in unemployment through two channels. First, responses to productivity shocks become more persistent as it takes time for agents to learn whether a shock is persistent or not. Second, noise shocks provide an additional source of persistence by amplifying the effects of on-the job search by affecting workers' search effort and firms vacancy posting decisions.

Keywords: Imperfect Information, Labor Market, Business Cycles

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1 Introduction

One of the well-established stylized facts in macroeconomics is the persistence in labor market dynamics; especially the sluggish recovery of unemployment following recessionary job losses. While the job losses at the onset of the recessions tend to normalize quickly, unemployment rate remains elevated much longer than the duration of the recession. Figure 1 shows that, it took the unemployment rate between 5 to 16 quarters to recover half of its recessionary increase and longer than 20 quarters to recover back to its pre-recession level. The duration for recovery has become even longer over time with the Great recession being the slowest. This stylized fact continues to present a challenge for conventional business cycle models (Cole and Rogerson (1999) and more recently Hall and Kudlyak (2022)).¹

I argue that imperfect information about the fundamental drivers of business cycles provides a natural explanation for sluggish recovery in the labor market even if the underlying shocks are not persistent. For example, Professional forecasters after the Great Recession, systematically over-estimated how high unemployment would be in the medium-run (see Figure 1). I proceed in two steps to establish the link between imperfect information and labor market dynamics. First, I identify noise shocks-errors in expectations due to the noise in received signals-using a structural VAR framework estimated with data on the utilization-adjusted TFP, real GDP growth and Nowcast errors for the period 1968-2019. I find that unemployment would have recovered to its pre-recession level 7 quarters earlier in the absence of noise shocks. Second, I introduce imperfect information using noise shocks along with permanent and transitory productivity shocks to a general equilibrium search model. The model extends the textbook model along three important dimensions: on-the-job search; endogenous search effort and rigid wages. I find that noise shocks together with these features provide an intuitive for the sluggish recovery of the labor market. Due to imperfect information, firms and workers observe noisy signals and cannot discern if the productivity shock is persistent or transitory. This affects forward looking decisions such as firms' hiring decisions and workers' job search decisions. Since firms and workers learn the true persistence of shocks only slowly, they respond sluggishly to changes in the economy which creates persistence in labor market dynamics.

I identify noise shocks using a using a tri-variate SVAR with utilization-adjusted TFP, real output and nowcast errors from the Survey of Professional Forecasters. The shocks are identified with a combination of sign restrictions and the max share identification, which optimizes the forecast error variance of a target variable (Francis et al., 2014). I consider three shocks: permanent and transitory productivity shocks and noise shocks. Noise shocks are assumed to only affect expectations about productivity but not to influence their actual levels. Therefore, noise shocks affect expected output growth more than actual output growth (Enders et al. (2021)). This assumption, along with the fact that the nowcast errors, that are defined as the difference in expected output growth from the realized output growth for the same quarter, are not available to the agents

¹The peculiar labor market dynamics in the wake of COVID pandemic presented a counter example which I address in Section 6.2.2.

contemporaneously, allows me to impose sign restrictions to identify the noise shocks. I then use the max-share method to disentangle the productivity shock into persistent and transitory components. I identify the shock that maximizes the forecast error variance of productivity in the long run as the persistent shock to productivity. I quantify the role of noise shocks in accounting for movements in the unemployment rate by computing the predicted unemployment rate due to only persistent and transitory shocks while shutting down the noise shock from the estimated SVAR. While it took on average 17 quarters for unemployment rate to recover 50% of its recessionary rise since the beginning of the recession, it would have been 11 quarters in the absence of noise shocks. Noise shocks also damped job-finding rates and vacancies.

I analyze the impulse responses for key labor market outcomes to the noise shock about the true persistence of productivity using smooth local projections (Barnichon and Brownlees, 2019). I find that noise shocks have persistent effects on the dynamics of the labor market. Specifically, a one standard deviation noise shock leads to an increase in the unemployment rate by 0.4 percentage points at 4 quarters and recovers between 8-10 quarters. This response results from an increase in inflow to unemployment and a decrease in job-finding rate, influenced by a decrease in vacancies and hiring rates by firms. Moreover, wage adjustment is sluggish, along with a decline in job-to-job transitions, contributing to this slow response of unemployment. These findings suggests that firms and workers overestimate the persistence of the true shock during these downturns and respond as if the recession was deeper and longer than it was. Firms reduce hiring and workers face lower job openings which keeps the unemployment rate persistently high.

There are two key takeaways from these impulse responses. First, the quantitatively and statistically significant response to a noise shock suggests the presence of information frictions. If firms and workers had perfect information about the shock being noise, first, noise shocks would not exist and, second, it would not be optimal for agents to respond to it since the fundamentals remain unchanged due to a noise shock. However, initially agents misperceive the noise shock as an actual negative productivity shock and hence firms decrease their hiring. As a result, there are fewer job opportunities for workers and job-finding rate decreases. This contributes to an increase in unemployment.

Second, the hump-shape of the impulse responses suggest that firms and workers are learning under imperfect information. Although firms and workers initially misperceive this shock as a change in fundamentals, they gradually place more weight on the shock being a noise shock. As a result, layoffs decline, hiring increases albeit slowly and the job-finding rate recovers. This ultimately results in a decline in unemployment.

Motivated by the empirical evidence, I set up a general equilibrium model of random search and matching with imperfect information. The model has several key features such as on-the-job search, endogenous search effort and wage rigidity. These choices are motivated by Cole and Rogerson (1999) who argued for incorporating heterogeneity in worker search intensity and allowing for on-the-job search as potential solutions to the slow recovery puzzle. Specifically, both unemployed and employed workers search and their search effort is endogenous. There

is a stylized job ladder with two kinds of jobs: good and bad jobs, which are idiosyncratic and revealed to the firms and workers upon matching. Good jobs offer higher wages and they hire both unemployed and employed workers. Bad jobs pay lower wages and only hire the unemployed. Employed workers in bad jobs search to move up the ladder and unemployed workers search to move to employment. Firms optimize hiring decision each period while incurring a cost of hiring. Wages are determined by staggered Nash bargaining a la Gertler and Trigari (2009) as they are only renegotiated with an exogenous probability. Therefore, on average wages exhibit sticky wages. There are two shocks: transitory and permanent productivity shocks. Moreover, there is imperfect information about the true nature of these shocks that I introduce to capture the noise shocks: workers and firms observe aggregate productivity but cannot distinguish between its transitory and permanent components. Instead, they receive a persistent noisy signal about the permanent component and use it to form beliefs about the future path of productivity. The persistent noise introduces complexity in determining whether a shock is a true persistent productivity shock or the persistence is due to noise. The model is calibrated by targeting key unconditional moments in the data and disciplined to match the empirical impulse responses of key labor market variables to the shocks identified from the SVAR. The model generates impulse responses consistent with the data, capturing both the magnitude as well as the hump-shape of the dynamic responses of key labor market outcomes such as unemployment, job-finding rate, job-to-job transition and vacancies.

I find that incorporating imperfect information about the underlying persistence of aggregate productivity shocks increases the persistence of unemployment relative to a full-information model where firms and workers can perfectly observe the persistent and transitory components of aggregate productivity each period, through two channels. First, the response to a persistent productivity shock in the model suggests that the effects of persistent productivity shocks are even more persistent because agents are learning about the true persistence of the shock. Agents initially attribute the shock to being persistent, transitory or noise with some probability, and under-react to the persistent shock as compared to the full information benchmark. For example, consider a negative persistent productivity shock. Wages do not decrease initially due to noise shocks making it hard to assess the true persistence of the shock. From the firms' perspective, if they adjust wages downward substantially and the shock reverses rapidly, their future discounted revenue will be lower since workers whose outside options improve would quit instead of waiting for wages to be renegotiated. Unemployed and employed workers do not decrease their search effort as much, since they attribute the shock to be noise with some probability. For the firms, although productivity is persistently lower with some probability, they have a higher pool of workers to match with, and therefore vacancies respond less than the full information model.

As firms and workers update their beliefs about the change in productivity being persistent or transitory, they assign more weight each period to the change in productivity being truly persistent. This adjustment in expectations is significantly slowed down by the persistence in the noise as agents now face a more complex signal extraction problem. This adds substantial persistence to the response of firms and workers relative to the full information model. Firms that get a

chance to renegotiate now offer lower wages as they assign higher weight to the shock being a true productivity shock and as a result the average wage decreases. Unemployed workers decrease their search effort as returns from employment declines. Further, employed workers looking to move up the ladder decrease their search effort as average wages have declined, it creates congestion for unemployment-to-employment transitions since most of the bad jobs remain occupied by the employed workers and good jobs are hard to find. This generates persistence in the job-finding rate, eventually leading to a more persistent response in unemployment than the full information counterpart.

The second channel is that the introduction of imperfect information gives rise to the noise shocks, which provide an independent source of persistence in the labor market. When there is a negative noise shock, agents partially attribute the perceived decline in productivity to an actual change in productivity, although the true productivity remains unchanged. This leads firms to anticipate diminished returns from new hires, assuming a less persistent level of future productivity, which subsequently reduces labor demand and the number of job vacancies. At the same time, unemployed workers, anticipating less favorable wage conditions due to the perceived fall in the persistent component of productivity, decrease their search intensities, lowering the rate at which jobs are found. Employed workers also decline their search effort as their incentive to move up the job ladder declines as anticipated wages decline. In equilibrium, these factors lead to fewer successful matches between firms and workers, thus increasing unemployment.

During downturns, both these channels act together to amplify the persistence of unemployment as firms and workers receive a sequence of all the shocks. Agents overestimate the persistence of a productivity shock due to presence of noise shocks, and perceive the negative productivity shock to be persistently worse than actual. Since they only learn over multiple periods whether a shock is persistent or transitory, this generates persistence as they keep responding as if facing a negative productivity shock which is more persistent than the true shock. Firms anticipate the productivity to be persistently worse than actual and furthermore, wages are slow to adjust downwards. Firms therefore expect lower future revenue and post fewer vacancies for longer than would be consistent with the true decline in productivity. Workers, expecting reduced wages, reduce their job search efforts. Employed workers who want to move up the ladder also search less, as anticipated returns from a good job is now decreasing, thereby resulting in fewer movements up the ladder. This creates a large pool of unemployed workers who do not immediately match as the probability of finding a higher productivity job is low. Overall job finding rate is dampened resulting in fewer employer-employee matches, thereby elevating unemployment rate. As agents slowly discern the actual persistence of the shock, unemployment persists longer than the productivity downturn alone would suggest.

Through a counterfactual exercise, the significant contribution of imperfect information to the persistence of unemployment rate, working through the mechanism described above becomes evident. I simulate the path of unemployment for recessions between 1968-2019, and find that, corresponding to the empirical findings, imperfect information with sticky wages and on-the-job

search predicts substantially higher persistence in the unemployment rate. On average it took 17 quarters from the beginning of the recession to recover 50% of the increase in unemployment. The imperfect information model with sticky wages and on-the-job search predicts this to be 14 quarters. Without imperfect information, this prediction would be 8 quarters. Finally, introduction of imperfect information improves upon the standard model with full information in explaining labor market volatility. The imperfect information model generates about 23% more volatility in unemployment rate as compared to the full information model. It also generates higher volatility in vacancies and transition rates, and a relatively lower volatility of wages, reflecting the observed volatility in the data.

1.1 Related Literature

This paper makes two significant contributions to the existing literature on labor market dynamics and business cycles. Firstly, it extends the work on the role of beliefs as drivers of business cycles (Beaudry and Portier, 2004; Collard et al., 2009; Blanchard et al., 2013; Forni et al., 2017; Chahrour and Jurado, 2018; Lagerborg et al., 2020; Ilut and Sajio, 2021), by specifically examining how imperfect information influences labor market fluctuations. In doing so, it complements studies that have focused on the role of beliefs in labor market dynamics (Den Haan and Kaltenbrunner, 2009; Theodoridis and Zanetti, 2016; Schaal, 2017; Chahrour et al., 2020). These papers primarily on anticipated news shocks about productivity, or uncertainty, that also propagate via agents' expectations, but do not necessarily imply imperfect information on part of agents. I contribute to this literature by identifying noise shocks that are an important source of aggregate fluctuations in the labor market.

This paper is closely related to Faccini and Melosi (2022) who also find that noise shocks play a significant role in the labor market dynamics. This paper also complements the findings in Morales-Jiménez (2022), where imperfect information is introduced in a search and matching model and finds that such a model is able to generate the volatility as well as elasticity of wages with respect to productivity consistent with the data. This paper also complements the findings in D'Agostino et al. (2022), who find that unanticipated changes in expectations display large and persistent effects on the unemployment rate during the Great Recession. I complement these papers by first proposing a novel identification for the noise shocks and documenting that imperfect information arising due to these noise shocks significantly affects firms' and workers' behaviors, leading to aggregate fluctuations across several recessions. Second, I document that introducing imperfect information in a search and matching model can predict higher persistence to better match the observed persistence of unemployment in recoveries from recessions.

It has been a feature of the postwar recoveries in the labor market that unemployment levels remains elevated, even after the initial spike in job destruction has subsided. Employment growth and job vacancies were also sluggish for multiple quarters following the trough in output. While there is consensus in the literature about these stylized facts and changes in unemployment dynamics, a unified consensus on the driver of slow recoveries remains elusive.

Some of the primary explanations that have been proposed for slow recoveries are job polarization (Jaimovich and Siu, 2020), restructuring² (Koenders et al., 2005; Berger et al., 2012), changing persistence of business cycles (Bachmann, 2012; Panovska, 2017) and increasing importance of technology shocks since mid-1980s (Barnichon, 2010b). Recent papers attribute the slow recoveries to UI extensions (Mitman and Rabinovich, 2019) and convergence of female employment (Fukui et al., 2023). This paper documents that noise shocks arising from imperfect information can substantially delay the recovery of the labor market, both empirically as well as quantitatively, thus contributing to this literature that has explored various aspects of labor market recovery patterns.

The rest of the paper is organized in the following manner. Section 2 discusses the empirical evidence and Section 3 discusses the identification of noise shocks using a structural VAR and its impact on labor market dynamics. Section 4 introduces imperfect information structure to a general equilibrium search and matching model. Section 5 discusses the calibration and estimation strategy for the model parameters. Section 6 presents the results from the quantitative exercise and Section 7 concludes.

2 Survey Forecasts and Recovery Pattern of the Labor Market

In this section, I first document the sluggish recovery pattern in the labor market and show that recoveries take on an average 25 quarters to recover to their pre-recession trough between 1968-2019. I then document the misperception about unemployment rate by professional forecasters across recessions and show that forecasters consistently predict longer recoveries in the labor market.

Recovery Duration of the Labor Market. The labor market recovery has been sluggish and unemployment rate remains high even after the job-destruction subsides. As a measure of this sluggishness, I compute the duration to recover the rise in unemployment across various recessions following Heise et al. (2022). I calculate the following $u_{recovery}$ duration to recover 25%, 50%, 75% and 100% rise in unemployment across recessions. These are reported in Table 1 and also plotted in Figure 1a.

$$u_{recovery} = \frac{u^{peak} - u_t}{u^{peak} - u_{trough}}$$

It took the unemployment rate between 5 to 16 quarters to recover half of its recessionary increase and longer than 20 quarters to recover back to its pre-recession level. Furthermore, a trend emerges: recoveries are becoming more protracted. On average, post-recession unemployment takes 10 quarters to reduce by 50% and 25 quarters for full recovery. Before 2000, 50% recovery occurred within 9 quarters; post-2000, this extends to 13 quarters, hinting at an increasing labor market persistence in recent periods.

²The long expansions caused the firms to hire workers not perfectly matched, creating an overhang at the end of expansions.

Table 1: Quarters Since the Peak to Recover the Rise in Unemployment Across Recessions

Recessions	(1) 25%	(2) 50%	(3) 75%	(4) 100%	(5) NBER Recovery
2007-09	9	16	21	33	25
2001	3	9	14	NA	40
1990-91	4	8	13	21	31
1981-82	4	5	15	22	4
1973-75	4	10	17	NA	12
1969-70	8	12	NA	NA	36
Average: Total	5	10	16	25	30
Average: Pre 2000	5	9	15	22	21
Average: Post 2000	6	13	18	33	33

Note: This table reports the number of quarters taken to recover the 25%, 50%, 70% and 100% of the rise in the unemployment rate from its peak, across recessions between 1968-2019, except the recession in 1980 which was quickly followed by the downturn in 1981-82. The NBER Cycle is the duration for economic activity to go from trough to its peak during each recession

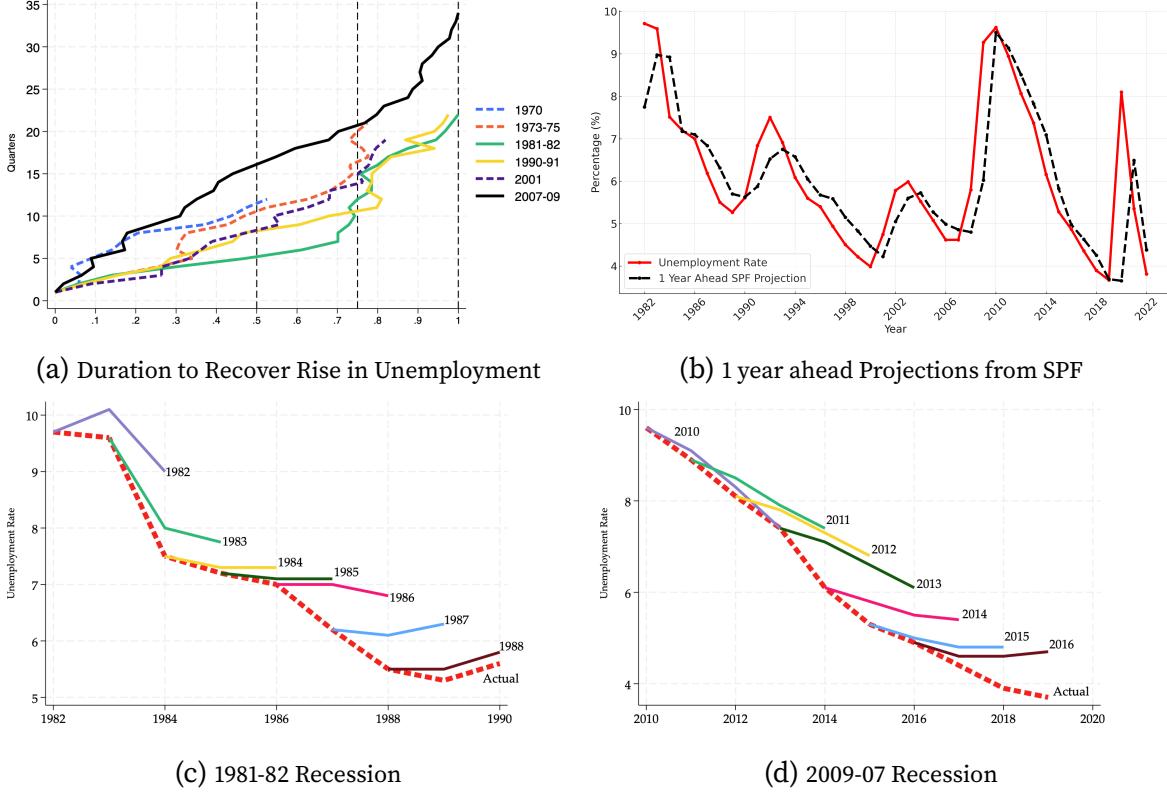
Forecast Errors and Misperception about Unemployment Rate. To understand whether economic agents misperceive the unemployment rate, I document the forecast errors from the Survey of Professional Forecasters. The Survey of Professional Forecasters (SPF) is a quarterly survey which elicits the expectations of professional forecasters about the state of the economy in the United States. It is often regarded as a benchmark as a measure of private sector expectations. Figure 1b plots the median 1 year ahead unemployment rate projections from the SPF, which documents that across recessions, forecasters predict the recovery to be slower than it is.

The SPF documents long run projections starting in 2009 and I report the long run projections in Figure 1d, where forecasters consistently overestimate the unemployment rate during the Great Recession—predicting a longer recovery than it actually transpired. This pattern can also be seen with older recessions such as the one in 1981-82, using the Livingston Survey that I document in Figure 1c. These figures suggest that there is a wedge between the expected and the actual unemployment rate, across recessions and across different Surveys.

One potential explanation for the observed wedge between realized and expected unemployment rates could be the imperfect information about whether the changes in the aggregate fundamental process in the economy is persistent or transitory (Edge et al., 2007). Due to imperfect information, agents must base their decisions on their expectations about the persistence of changes in the true fundamental process, by observing some signals. Under such a framework, agents then may predict consistently higher unemployment rate as they cannot distinguish the true shocks in the economy from noise shocks: errors in expectations due to the noise in received signals. To test this hypothesis, I proceed in two steps. I first identify the noise shocks using a SVAR that I discuss in the following section. And then, I study whether the aggregate labor market outcomes respond to the identified shocks.

Now, to identify the noise shocks, one would need a measure of misperception of the agents. Following Enders et al. (2021), I thus use the ‘nowcast error’—the difference between actual output

Figure 1: Unemployment Rate: Projections and Recovery



Note: In Panel (a), I plot the number of quarters it took to recover the rise in unemployment rate across recessions between 1968-2019 (except the 1980 recession). The vertical lines represent the 50%, 75% and 100% of the total recovery. In Panel (b), I plot the 1-year ahead unemployment projections that are reported from the Survey of Professional Forecasters. In Panel (c), the various colored lines represents the median 1 and 2 year ahead projection of unemployment rate from the Livingston Survey. The solid red line is the actual unemployment rate during the 1981-82 recession. In Panel (d) The various colored lines represents the median long-run (1 year, 2 year and 3 year ahead) projections of unemployment rate from the Survey of Professional Forecasters during the Great Recession. The dashed red line is the actual unemployment rate.

growth and real-time perceived output growth—for identifying the noise shocks, since these contain important information about the real-time misperceptions of professional forecasters.

Nowcast Errors The nowcasts, which are median expectations about the current GDP growth, are collected from the Survey of Professional Forecasters. The nowcast errors are computed as the difference between the current GDP growth and the median GDP growth nowcast. For the rest of the paper, it is defined as

$$(1) \quad nce_t = \Delta y_t - \mathbf{E}_t^{\text{median}}(\Delta y_t)$$

where y_t is the current real GDP growth. The timing of the survey is such that the participating professional forecasters are asked to report their expectations about the current quarter output growth by the second month of the quarter. At this point, no information regarding current output

is available.³ Thus, at time t , the nowcast errors are not available in real time and hence are not part of any agent's information set. This gives an informational advantage to the econometric over economic agents as the nowcast errors only become available ex-post. As noted by Enders et al. (2021), this plays a key role in the identification of noise shocks.

3 Identification of Noise Shocks

In this section, I test the hypothesis that the observed wedge between realized and expected unemployment rates arise due to imperfect information about whether the changes in the aggregate fundamental process in the economy is persistent or transitory. I proceed in two steps. First, I identify the noise shocks using a tri-variate SVAR. The identification of noise shocks is achieved by imposing sign and zero restrictions. Then, I identify persistent and transitory productivity shocks by maximising the forecast error variance of aggregate productivity in the long run. Second, using local projections, I find that the noise shocks have a significant effects on the dynamics of key labor market indicators like unemployment and vacancies.

Empirical Specification. The aggregate productivity process is typically assumed to consist of a persistent and a transitory component. However, productivity is not observed perfectly contemporaneously in the model. Therefore, economic agents must form their beliefs about aggregate productivity using public signals. A shock to the signal is defined as a noise shock, as it affects beliefs of agents independent of any changes in actual productivity. The aim is to now identify the three shocks, a persistent shock to aggregate productivity, a transitory shock to aggregate productivity and a noise shock. The empirical specification consists of a vector-autoregression of the form

$$(2) \quad A_0 \mathbf{Y}_t = a + \sum_{j=1}^p A_j \mathbf{Y}_{t-j} + e_t$$

where the set of variables $\mathbf{Y}_t \equiv [TFP_t, GDP_t, NCE_t]$ includes the utilization-adjusted TFP from Fernald (2014), real GDP growth and Nowcast errors.⁴ The sample period ranges from 1968q4 to 2019q4. A_j is the weight on past realizations of Y_t , e_t is a vector of structural economic shocks, and A_0^{-1} is the structural matrix that the SVAR procedure seeks to identify from the set of reduced-form residuals. The fact that agents cannot observe the nowcast errors in real time provides the econometrician an informational advantage over the economic participants in real time, thus making the SVAR model invertible (Blanchard et al., 2013).

³The release from the Bureau of Economic Analysis (BEA) is at the end of the current quarter. The only source of information that the forecasters might use in order to nowcast output growth for the current quarter, is the NIPA advance report regarding output in the previous quarter.

⁴The fact that the VAR does not include any labor market outcomes such as the unemployment rate, allows the identified shocks to be unaffected by fluctuations in the labor market directly.

It follows that the reduced-form representation is

$$(3) \quad y_t = b + \sum_{j=1}^p B_j y_{t-j} + u_t$$

Here $b = A_0^{-1}$ is an $n \times 1$ vector of constants, $B_j = A_0^{-1}A_j$, $u_t = A_0^{-1}\epsilon_t$. $\text{var}(\mathbf{u}_t) = E(\mathbf{u}_t\mathbf{u}_t') = \Sigma = \mathbf{A}_0^{-1}(\mathbf{A}_0^{-1})'$ is the $n \times n$ variance-covariance matrix of reduced-form errors. Let $\phi = (\mathbf{B}, \Sigma)$ collect the reduced-form parameters. Finally, following Uhlig (2005), I define the set of all IRFs through an $n \times n$ orthonormal matrix $\mathbf{Q} \in \Theta(n)$ where $\Theta(n)$ is the set of all $n \times n$ orthonormal matrices.

Identification Assumptions Aggregate belief shocks in an imperfect information structure are identified in the data using a combination of sign restrictions and max share identification in a trivariate structural VAR. The sign restrictions identify the noise shock and the max-share approach identifies the persistent shocks from the transitory productivity shocks.

1. I impose the following restrictions on the impact matrix to identify the noise shocks.

- (a) Noise shock has zero impact on aggregate productivity. Noise is an error in the expectations of economic agents. It should not affect the underlying fundamental productivity process in the economy which is the total factor productivity here.
- (b) On impact, the persistent and the transitory TFP shocks contemporaneously affect TFP and GDP growth in the same direction. The response of the nowcast error to a persistent as well as a transitory shock is unrestricted.⁵
- (c) Noise shock contemporaneously affects nowcast errors in the opposite direction as the GDP growth. Noise shocks cause a smaller change in actual GDP growth than they do in expectations. In other words, this implies that noise shocks are assumed to move expectation about real GDP more than real GDP itself. GDP also increases as agents respond but it increases less than the expectations. This implies that $nce_t = \Delta y_t - \mathbf{E}_t^{\text{median}}(\Delta y_t) < 0$ while $\Delta y_t > 0$. This assumption is also supported by Enders et al. (2021) and Chahrour et al. (2021) who identify belief shocks in a bi-variate VAR using sign restrictions.

These identifying restrictions hold across a broad class of models with information structures consistent with Lorenzoni (2009), Blanchard et al. (2013), and Angeletos and La'o (2010). Let ϵ_t be the persistent shock, η_t be the transitory shock and ν_t be the noise shock. Thus, the restrictions on the impact matrix can be demonstrated by the following:

⁵A TFP shock *may* cause a larger change in actual GDP growth than it does in expectations as evidence suggests that consensus forecasts under-react relative to full-information rational expectations (Bordalo et al., 2020). For robustness, I consider an alternate specification where I impose the restriction that the TFP shocks affects the nowcast error in the same direction as TFP and output. However, since the identification of the persistent or the transitory shock does not depend on the sign restrictions, the results from this exercise are in line with the main exercise.

$$(4) \quad \begin{bmatrix} z_t \\ y_t \\ nce_t \end{bmatrix} = \Sigma_j^p B_j \begin{bmatrix} z_{t-p} \\ y_{t-p} \\ nce_{t-p} \end{bmatrix} + \begin{bmatrix} + & + & 0 \\ + & + & + \\ * & * & - \end{bmatrix} \begin{bmatrix} \epsilon_t \\ \eta_t \\ \nu_t \end{bmatrix}$$

2. The sign restrictions identify the noise shocks, but do not distinguish between the persistent and the transitory shock. To identify the persistent shock from the transitory shock, I use what is referred to as the *max-share* identification strategy in the literature. I extract the persistent shock as the innovation that accounts for the maximum forecast error variance (FEV) share of utilization adjusted TFP at a long but finite horizon. This method builds on Uhlig et al. (2004), and has been used by Francis et al. (2014) to identify long run TFP shocks. More recently this has been used by Kurmann and Sims (2021) in context of news shocks.

Now, to formalize the identification strategy described above, let $j \in \{1, 2, 3\}$ be the shocks, and $i \in \{1, 2, 3\}$ denote the TFP, GDP growth and nowcast error respectively. Define $I_{-j} = 1, \dots, k$ as a subset of the shocks of interest. Let s_{jh} be the sign restrictions on the impulse response vector to the j^{th} structural shock at horizon h . In this case, the impulse response is given by the j^{th} column vector of $\mathbf{IR}^h = \mathbf{C}_h(\mathbf{B})\Sigma_{\text{tr}}\mathbf{Q}$. The sign restrictions are represented by $\mathbf{S}_j(\Phi)\mathbf{q}_j \geq \mathbf{0}$, for $j \in \mathcal{I}_S$. Let $\text{CEFEV}_j^i(H)$ denote the factor error variance (% contribution) at horizon H of variable i explained by the j^{th} structural shock.

$$(5) \quad \text{CEFEV}_j^i(H) = q'_j \Gamma^i(\Phi) q_j \quad ; \quad \Gamma_H^i(\Phi) = \frac{\sum_{h=0}^H c_{ih}(\Phi) c'_{ih}(\Phi)}{\sum_{h=0}^H c'_{ih}(\Phi) c_{ih}(\Phi)}$$

where $\Gamma_H^i(\Phi)$ is $n \times n$ positive semi-definite matrix.

Thus, the identification of the three shocks, $\mathbf{Q}_{1:k} = [\mathbf{q}_1, \mathbf{q}_2, \dots, \mathbf{q}_k]$ requires us to solve the following problem

$$(6) \quad \mathbf{q}_1^* = \arg \max_{\mathbf{q}_1} \mathbf{q}'_1 \Gamma_H^1(\Phi) \mathbf{q}_1$$

subject to

$$(7) \quad \mathbf{q}'_1(1, 3) = 0$$

$$(8) \quad \mathbf{S}_j(\Phi) \mathbf{q}_j \geq \mathbf{0}, \text{ for } j \in \mathcal{I}_S$$

$$(9) \quad q'_1 q_1 = 1$$

Here the horizon is assumed to be $H = 40$ quarters, which is a medium run horizon. This is because the effects of transitory and noise shocks are not expected to persist for as long as a decade.⁶ Now, this implies that the shock can only be extracted till 2012. To extend the series, for

⁶The results are robust to longer horizons, up to $H = 60$ quarters.

2012-2019, I calculate H as the maximum available horizon from that point. In 2017, this is set to $H = 20$. As seen in Appendix Figure A7, persistent shock explains the maximum variance of TFP even at 20 quarters. Equation 7 is the restriction that noise shocks have zero effect on TFP, which follows from the definition of the noise shock. Equation 8 consists of the sign restrictions detailed in equation 4. Equation 9 ensures that the identified shocks are mutually orthogonal. I follow the algorithm outlined by Carriero and Volpicella (2022) to solve this optimization problem. I assume 4 lags as suggested by the Akaike Information Criterion and uniform priors.

The impulse response of the nowcast errors to the identified shocks suggests that forecasters do not have full information about the economy. Appendix Figure A6 shows the impulse response of TFP, GDP growth and nowcast errors to the identified persistent, transitory and noise shocks. The nowcast error increases on impact of the persistent shock, but does not recover immediately in the next period. Furthermore, the nowcast error responds weakly to the transitory shock on impact and has a delayed positive response. This signifies that forecasters can not distinguish immediately if a shock is persistent, transitory or noise, and learn with some persistence. Noise shocks have a negative effect on impact on the nowcast errors since this is a restriction imposed by the VAR.

Predictably, the positive persistent shock increases TFP as on impact and declines persistently. GDP growth weakly responds to a persistent productivity shock on impact, but has a delayed positive and persistent response. A transitory shock increases TFP and GDP Growth on impact but the effect is not persistent. Finally, TFP does not respond to noise shocks, in line with the zero restriction imposed. Noise shock has a positive and somewhat persistent effect on GDP growth.

3.1 Effect of Noise Shocks on Labor Market Dynamics

Key labor market variables exhibit significantly persistent impulse responses to the identified noise shocks at the business cycle frequency (8-10 quarters). Historical decomposition shows that noise shocks have an increasingly important role to play in the evolution of unemployment, vacancies and job finding rates over the business cycle which is a motivation to introduce imperfect information in a search and matching model.

Smooth Local Projections Once the shocks are extracted from the VAR, I can now study how labor market variables respond to these shocks using smooth local projections (SLP) (Barnichon and Brownlees, 2019). For each shock u_j , the Jordà (2005) local projections are given by

$$(10) \quad y_{t+h} = \alpha_h^j + \beta_h^j u_t^j + \sum_{p=1}^P \gamma_p^j \omega_{t-p} + \mu_{h,t+h}^j$$

where ω_{t-p}^j is the set of lagged values of y and u^j .

Following Barnichon and Brownlees (2019), one can approximate $\beta_h^j \approx \sum_{k=1}^K b_k^j B_k^j(h)$ using

a linear B-splines basis function expansion in the forecast horizon h . Thus, the corresponding smooth Linear Projections can be written as Equation 11.

$$(11) \quad y_{t+h} \approx \sum_{k=1}^K a_k^j B_k(h)^j + \sum_{k=1}^K b_k^j B_k^j(h) u_t^j + \sum_{p=1}^P \sum_{k=1}^K c_{pk}^j B_k^j(h) \omega_{t-p}^j + \mu_{h,t+h}^j$$

The SLP is estimated using generalized ridge estimation and further details can be found in Appendix section A.5 and Barnichon and Brownlees (2019).

Here, y_t = aggregate labor market outcomes such as unemployment rate, vacancies, rate of outflow from unemployment (UE), job-to-job transition rates (EE), hiring rate and wage growth. u_t^j are the three shocks respectively while μ_t^j is the residual error for each regression. All labor market data are from Current Population Survey and JOLTS for vacancies and hiring rate.⁷ Figures 2 and 3 show the impulse responses of the labor market variables to noise and persistent TFP shocks.⁸

Figure 2: Impulse Response to Noise Shocks



Note: This figure plots the smoothed cumulative impulse response functions for key labor market variables to a noise shock, estimated using equation 10, where u_t^j is the noise shock identified using the SVAR described by the optimization problem in equation 6. The sample period is 1968q4: 2019q4. Data for the labor market outcomes are from CPS, vacancies from Barnichon (2010a) and wages from BEA's average hourly earnings series. The shaded area represents a 95% confidence interval.

Noise shocks have a significant and persistent effect on unemployment, vacancies, UE , EE as well as hiring rate for upto 8-10 quarters. The effect on wage growth is delayed, although weak,

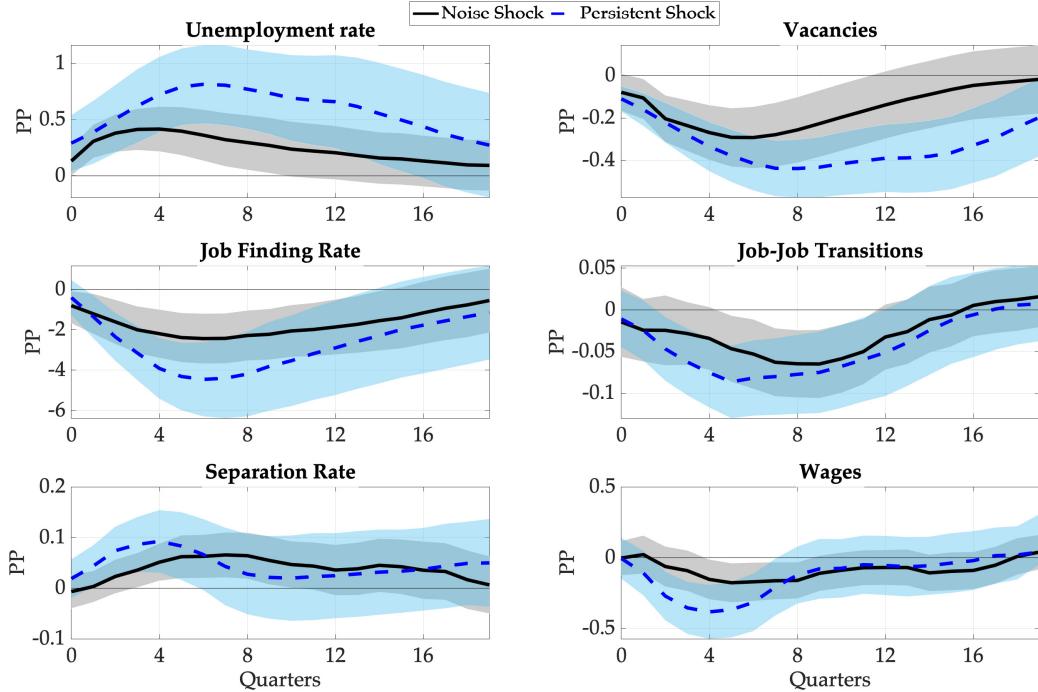
⁷The results are consistent with using an Autoregressive Distributed Lag (ADL) specification for local projections.

⁸Response to the transitory TFP shocks is documented in Appendix Figure A9.

indicating that wages are sluggish. Unemployment rises by 0.6 percentage points in response to a one standard deviation noise shock. The number of job vacancies decreases, and transitions from unemployment to employment reduce. Job-to-job transitions also decline.

These results suggest that agents cannot distinguish the type of shock they face correctly and that they learn slowly over time about the true shocks. The hump shape of the impulse responses suggest that initially agents misperceive the noise shock as an actual negative productivity shock and hence respond as if faced with an actual negative productivity shock. Firms decrease their hiring and increase layoffs. As there are less jobs to be matched with now, the job finding rate decreases and translates to an increase in unemployment. However, as firms and workers learn about the true process in the economy, they place higher weight on the shock being a noise shock and gradually start increasing hiring. As a result, outflow from unemployment increase, resulting in a decline in unemployment.

Figure 3: Impulse Response to Persistent TFP Shocks



Note: This figure plots the smoothed cumulative impulse response functions for key labor market variables to a persistent TFP shock (in blue), estimated using equation 10, where u_t is the persistent TFP shock identified using the SVAR described by the optimization problem in equation 6. The 95% confidence interval is shaded in blue as well. It is superimposed on the IRFs from the noise shocks in Figure 2. The sample period is 1968q4: 2019q4. Data for the labor market outcomes are from CPS, vacancies from Barnichon (2010a) and wages from BEA's average hourly earnings series. The shaded area represents a 95% confidence interval.

These results are consistent with learning which motivates the introducing of imperfect information in a general equilibrium model of search and matching. If there was complete information in the economy firms and workers would not respond to noise shocks because these don't change

the fundamental economic conditions. Moreover, the time it takes for the impulse responses to recover, suggests that this learning process is quite gradual. If learning happened more rapidly, the economy would adjust to noise shocks much faster.

Forecast Error Variance Decomposition The forecast error variance decomposition is informative of the variance in an outcome explained by each of the shocks at a specific horizon. I use the estimator proposed by Gorodnichenko and Lee (2020) for calculating the forecast error variance decomposition with local projections. The forecast error for the h -period ahead value of an endogenous variable y_t is given by

$$(12) \quad f_{t+h|t-1} \equiv (y_{t+h} - y_{t-1}) - P[y_{t+h} - y_{t-1} | \Omega_{t-1}]$$

where $P[y_{t+h} - y_{t-1} | \Omega_{t-1}]$ is the projection of $y_{t+h} - y_{t-1}$ on the information set $\Omega_{t-1} \equiv \{\Delta y_{t-1}, \mu_{t-1}, \Delta y_{t-2}, \mu_{t-2}, \dots\}$. The forecast errors due to innovations in μ can be decomposed as follows:

$$(13) \quad f_{t+h|t-1} = \psi_{\mu,0}\mu_{t+h} + \dots + \psi_{\mu,h}\mu_t + v_{t+h|t-1}$$

where $v_{t+h|t-1}$ is the error term due to innovations orthogonal to $\{\mu_t, \mu_{t+1}, \dots, z_{t+h}\}$ and Ω_{t-1} .

The share of variances explained by the contemporaneous and future innovations in μ_t to the total variations in $f_{t+h|t-1}$ can be defined as follows (Sims, 1980):

$$(14) \quad s_h = \frac{\text{var}(\psi_{\mu,0}\mu_{t+h} + \dots + \psi_{\mu,h}\mu_t)}{\text{var}(f_{t+h|t-1})}$$

s_h in equation 14 is estimated using the coefficient of determination estimator for FEVDs as proposed by Gorodnichenko and Lee (2020). The result of this exercise is summarized in Table 2.

The FEVD analysis reveals that at a short-run horizon of 0 to 8 quarters, noise shocks are notably influential in accounting for the variability in key labor market metrics such as unemployment, job openings, inflows and outflows from unemployment, and rates of transitions between jobs. Specifically, at an 8-quarter average, noise shocks account for 34% of the variation in unemployment, 37% in job vacancies, 35% in the outflow rate from unemployment, 27% in employment-to-employment transitions, and 14% in wage growth.

While persistent factors generally make up a larger share, ranging from 38% to 61% across these indicators, and transitory factors contribute between 21% and 31%, the influence of noise shocks is substantial. Especially in terms of job vacancies and unemployment, noise shocks account for more than one-third of the observed variability, highlighting their significant role in short-term fluctuations in the labor market.

At a longer run horizon of 8-16 quarters, persistent shocks are the primary drivers of variance across all labor market indicators. Specifically, they account for 63% of the variation in unemployment, 61% in vacancies, 63% in the job-finding rate, 65% in job-to-job transitions (*EE*), and 92% in wage changes. Predictably, noise shocks show a comparatively modest influence, accounting for

Table 2: Forecast Error Variance Decomposition: Shorter Run Horizon

	Short Run			Medium Run		
	Horizon: 0-8 quarters			Horizon: 9-16 quarters		
	Persistent	Transitory	Noise	Persistent	Transitory	Noise
Unemployment	0.41	0.23	0.34	0.63	0.21	0.16
Vacancies	0.42	0.21	0.37	0.61	0.20	0.19
UE	0.38	0.27	0.35	0.63	0.20	0.17
EE	0.42	0.31	0.27	0.65	0.16	0.19
Wage Growth	0.61	0.25	0.14	0.92	0.05	0.03

Note: This table reports the average forecast error variance decomposition for U , V , $E - E$, $U - E$ and ΔW , estimated using equation 14, over a short run (0-8 quarters) and a medium run (8-16 quarters) horizon. Each row adds to 1. Noise shocks explain a significant variation in the labor market at a short run horizon. The sample period is 1968q4: 2019q4. Data for the labor market outcomes are from CPS, vacancies from Barnichon (2010a) and wages from BEA's average hourly earnings series.

15-19% of the variance in unemployment, vacancies, job-finding rate, and EE transitions, and 3% in wages. Transitory shocks play a less substantial role, contributing to less than 25% of the variance in unemployment, vacancies, UE , and EE transitions respectively, and only 5% in wage growth.

Historical Contribution of Noise Shocks. To understand the role of imperfect information over the business cycle, it is useful to understand how much of the deviation of the key labor market outcomes from their predicted path can be explained by the productivity shocks. If noise shocks are not important, the productivity shocks would explain almost all the fluctuations in these variables. Here, the decomposition for $j = \{1, 2, 3\}$ shocks can be written as the following:

$$(15) \quad y_t - \bar{\Psi}_t = \sum_j \sum_{h=0}^{t-t_0} \beta_h \cdot \mu_{j,t-h}$$

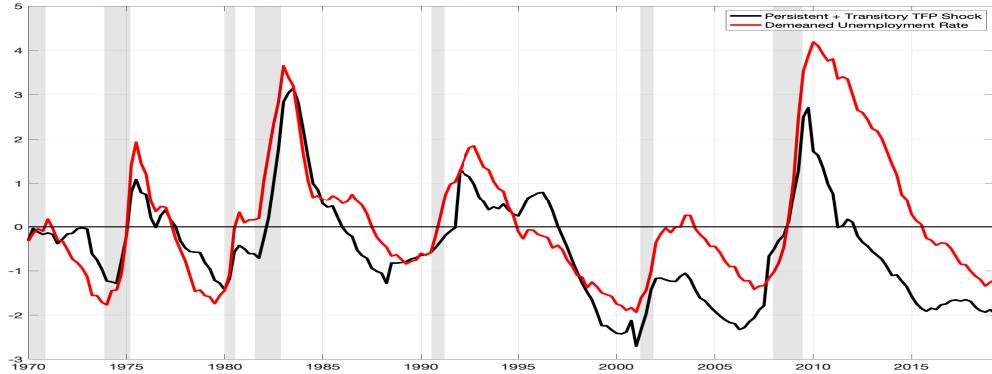
where, $\bar{\Psi}_t$ is the pure deterministic component and y_t is various labor market outcomes such as unemployment rate, vacancy postings, job finding rate and average hourly earnings.

Two key facts emerge from the historical decomposition: first, that the productivity shocks alone fail to account for the persistence of unemployment rate post 1985, and second, that noise shocks have been playing an increasingly important role since 1990s. Figure 4a plots the deviation of unemployment rate from its predicted path due to the persistent and transitory productivity shocks alone. Thus, the remaining movement is explained by the noise shocks.

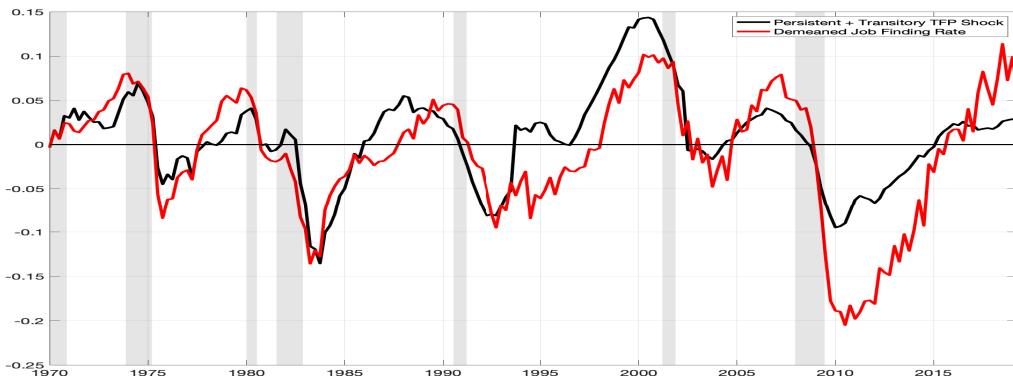
An examination of the recessions in 1990, 2001, and 2007-09 reveals that the productivity shocks are insufficient to completely explain the fluctuations in the unemployment rate, vacancy postings and job finding rates. The productivity shocks predicted a faster recovery across these recessions and a diminished peak during the Great Recession. Moreover, Figure 1d demonstrates that professional forecasters during the Great Recession anticipated unemployment rates that were both higher and more persistent than the actual unemployment rate.

Figure 4: Historical Contribution of Persistent and Transitory TFP Shocks

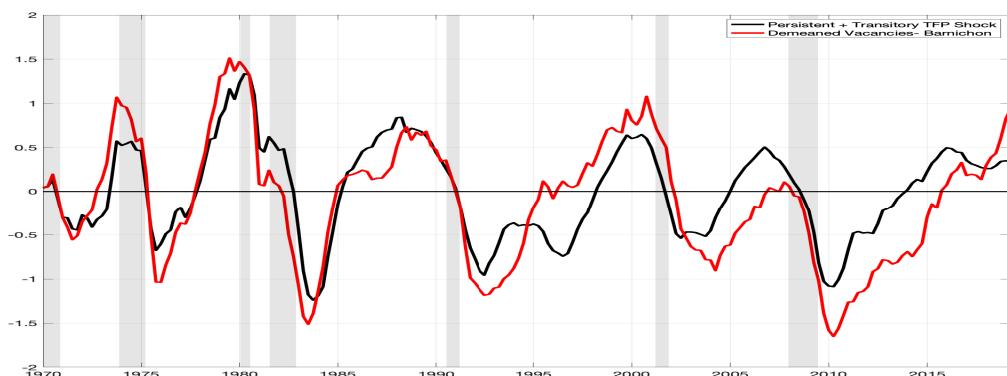
(a) Unemployment Rate



(b) Outflow from Unemployment



(c) Vacancies



Note: This figure plots the historical decomposition of unemployment rate, vacancy postings and outflow rate from unemployment following equation 15. The black line is the cumulative contribution of the identified persistent and transitory TFP shocks to the movements in the demeaned vacancy postings (red line). The remaining movement is explained by the noise shocks, which contribute significantly to the vacancy postings during the recessions in 1990-91, 2001 and 2007-09.

Outflow from unemployment and vacancies follows a similar pattern, where the fundamental shocks do not fully explain the fluctuation as well as the speed of the recovery. Noise shocks dampened the job finding rates during the expansion in the 90s, but amplified the vacancy postings. There seems to be a disconnect between the effect of imperfect information during expansions on households and firms, but during the downturns, noise shocks consistently amplify the decline in both job finding rates as well as vacancy postings.

An aggregate assessment of these findings implies that during these recessions, noise shocks led to a mis-estimation of the persistence of the shock by economic agents. This misperception led to an overestimation of the actual persistence of the shock, thereby influencing decisions concerning employment and production. In other words, firms and workers perceived the recessions to be worse than they actually were. Consequently, there was a more pronounced reduction in vacancy postings, accompanied by a decrease in job-finding rates. These factors together resulted in unemployment levels that were not only elevated but also persistent, reflecting a persistence that was greater than originally anticipated.

To understand the contribution of the noise shocks to the persistence of unemployment, I compute for each recession between 1968-2019, the share of the rise in unemployment during the recession that has been reversed during the expansion (Heise et al., 2022).

$$u_{recovery,t} = \frac{u_{peak} - u_t}{u_{peak} - u_{trough}}$$

I then define persistence as the number of quarters to recover 50% of the rise in unemployment during a recession, that is $u_{recovery,t} = 0.5$. Now, from the historical decomposition, I can calculate what fraction of this persistence can be attributed to each of the shock by first computing the predicted unemployment rate from each shock and then calculating the persistence as defined above. The results are summarized in Appendix Table A2. For the great recession, noise shocks account for about 35% of the 50% of the rise in unemployment and on average noise shocks account for 27% of this recovery across recessions.

The second observation that emerges from this analysis is that the role of noise shocks appears to be more prominent post the Great Moderation. Figure A5 plots the shock series retrieved from the VAR and as can be seen, the noise shocks during the three recessions post 1990 had a larger negative draw than in the pre 1990 decades. Interestingly, the persistent shock displays the opposite pattern. This merely demonstrates that noise shocks have had a larger role to play post 1990, although the time-series is not long enough to establish if this is a systematic pattern. Pre-2000 it took on average 26 quarters for the unemployment rate to recover to its pre-recession trough while after 2000 it took 32 quarters. On average, noise shocks explain 19% of this recovery duration pre-2000, and 36% of this duration for the post-2000 recessions.

The empirical results indicate that noise shocks play a significant role in explaining the dynamics of the labor market over the business cycle and specifically the sluggish recovery from recessions. Now, to understand the mechanism through which noise shocks affect the persistence

of the labor market, I introduce imperfect information in a general equilibrium model of search and matching in the following section.

3.2 Robustness Exercise: Inclusion of Unrestricted Shocks

Structural shocks do not satisfy the sign restrictions for the noise shocks, since any structural shock results in a larger change in actual output than expected. However, there may be potentially other shocks such as monetary policy shocks or financial shocks, not included in the SVAR, which may behave like the noise shocks. To address this concern, I include a fourth unrestricted shock in the system. The key argument here is that if there are other shocks that are being picked up by any of the persistent, transitory or noise shocks, inclusion of the fourth shock should then account for those shocks. I include unemployment as the fourth variable and leave unrestricted the impact matrix. The modified VAR is thus given by equation 16.

$$(16) \quad \begin{bmatrix} z_t \\ y_t \\ nce_t \\ u_t \end{bmatrix} = \sum_j^p B_j \begin{bmatrix} z_{t-p} \\ y_{t-p} \\ nce_{t-p} \\ u_{t-p} \end{bmatrix} + \begin{bmatrix} + & + & 0 \\ + & + & + \\ * & * & - \\ * & * & * \end{bmatrix} \begin{bmatrix} \epsilon_t \\ \eta_t \\ \nu_t \\ \mu_t \end{bmatrix}$$

Once again, I assume that ϵ_t maximizes the forecast error variance of TFP at a long run horizon. I present here the result of the historical decomposition exercise in Figure 5. Here as we see, the noise shocks still explain a significant variation in unemployment rate. However, in the 1973-75, as well as the 1980-81, 1982-83 recessions, the contribution of the 4th shock is the highest in explaining the movement in unemployment rate. This is consistent with the fact that these recessions were mostly explained by monetary policy shocks or oil shocks, which cannot be attributed to TFP shocks.

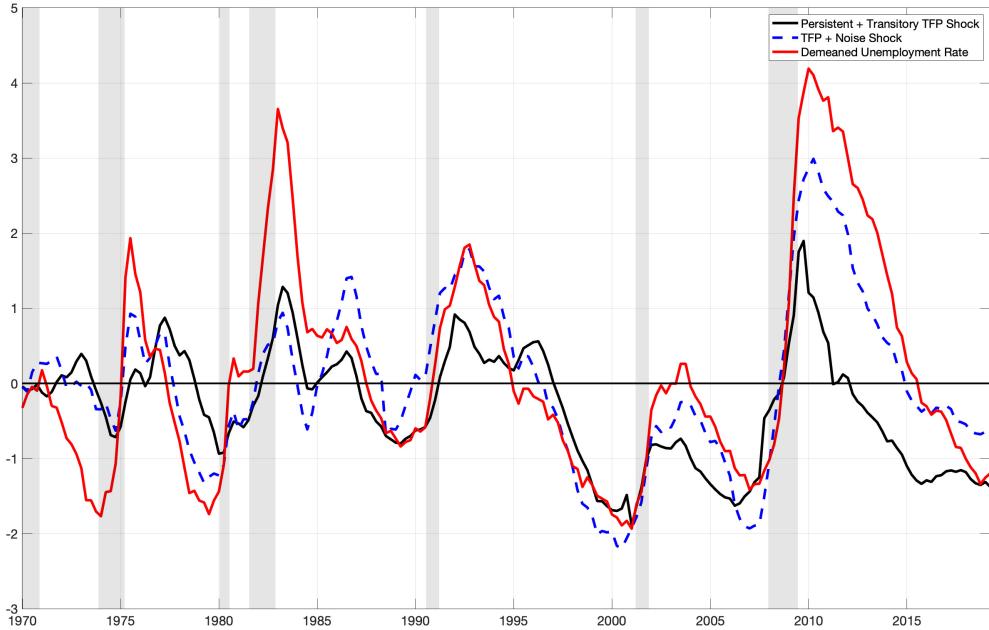
4 A Search and Matching Model with Information Frictions

Standard models of search-and-matching fail to fully explain the volatility of unemployment and vacancies as well as the slow recovery of the labor market from recessions Cole and Rogerson (1999).⁹ Motivated by the empirical evidence that imperfect information plays an important role in explaining these dynamics, this section introduces an imperfect information structure to a search and matching model.

The model is based on a real business cycle model with search and matching in the labor market as in Merz (1995) and Andolfatto (1996) and follows the extensions by Gertler et al. (2020) who introduce staggered wage contracting and allow for on-the-job search with variable intensity. The primary reason for introducing a staggered wage contracting in the context of this paper is that

⁹As Cole and Rogerson (1999) note, the DMP model can account for business cycle facts only if the average duration of non-employment spell is nine months or longer, which is quite high than observed in the data.

Figure 5: 4 Variable VAR: Historical Contribution of Shocks to Unemployment Rate



Note: This figure plots the historical decomposition of unemployment rate following equation 15. The black line is the cumulative contribution of the identified persistent and transitory TFP shocks to the movements in demeaned unemployment rate (red line). The dashed blue line is the contribution of the TFP shock and the noise shocks, which contribute significantly to the unemployment rate during the recessions in 1990-91, 2001 and 2007-09. The remaining movement here is explained by the 4th shock μ_t .

wage rigidity amplifies the role of imperfect information, as will become clear in the subsequent subsections (Chahrour and Jurado, 2018; Morales-Jiménez, 2022). The reason for introducing endogenous search effort as well as on-the-job search, is to capture the response coming from workers when faced with information frictions. Job-to-job transitions capture not only the cyclical wage gains, but also crowd out unemployed workers searching for a job, thus capturing an important moment of the labor market. In the following sub-sections I describe the environment for the model and discuss the problems of firms and households.

Environment There is a continuum of firms and workers, each of measure unity. Firms that post vacancies and workers looking for jobs meet randomly. The aggregate productivity in the economy is given by z_t . Idiosyncratic match quality is revealed once a worker and a firm meet. Match quality of a worker within the firm is either good (g) with probability ξ , or bad (b) with probability $1 - \xi$. The productivity of a bad match is a fraction ϕ of the productivity of a good match, where $\phi \in (0, 1)$. The firms' effective labor force is

$$(17) \quad l_t = g_t + \phi b_t$$

The total number if unemployed workers is given by:

$$\begin{aligned}\bar{u}_t &= 1 - \bar{n}_t - \bar{b}_t \\ \bar{n}_t &= \int_i n_t di \\ \bar{b}_t &= \int_i b_t di\end{aligned}$$

where \bar{n}_t and \bar{b}_t are the total number of workers in good and bad matches respectively across all firms, indexed by i .

Workers search for jobs when they are unemployed with endogenous search intensity ζ_u . Employed workers in a bad match also search on the job so that they can move up the ladder and match with a good job. They search with endogenous search intensity ζ_b . Workers searching on the job only transition to good jobs. If they are matched with another bad job, they stay in their current bad jobs and hence lateral moveemnts to other bad jobs are eliminated.¹⁰ Search is costly and the cost of searching is characterized by

$$c(\zeta_{jt}) = \mu(\zeta_{jt})^{\frac{1}{1+\omega}}$$

where, ζ_{jt} is the search intensity of unemployed workers ($j = u$) and employed workers in bad matches ($j = b$). There are two ways a match can be dissolved. First, firms and workers may receive an exogenous separation shock with probability $1 - \sigma$. Workers who receive the separation shock become unemployed at the beginning of next period. Second, if the match is not destroyed, a worker in a bad match searches on the job. If she finds another job and accepts it, the worker moves to the new firm within the period and the match with the current employer is dissolved. The total efficiency units of search is therefore given by the search intensity weighted sum of searchers

$$\bar{s}_t = \zeta_{ut} \bar{u}_t + \sigma \zeta_{bt} \bar{b}_t$$

The aggregate number of matches are thus a function of the efficiency weighted number of searchers \bar{s}_t and the number of vacancies \bar{v}_t :

$$\bar{m}_t = \Psi \bar{s}_t^\alpha \bar{v}_t^{1-\alpha}$$

where α is the elasticity of matches to units of search and Ψ is the matching efficiency. The probability that a unit of search leads to a match is given by

$$p_t = \frac{\bar{m}_t}{\bar{s}_t}$$

¹⁰As Gertler et al. (2020) explain, the expected gain from a lateral move is quantitatively trivial and can be ruled out with a small moving cost.

It follows that the probability that the match is good (p_t^g) or bad (p_t^b) is as follows respectively

$$\begin{aligned} p_t^g &= \xi p_t \\ p_t^b &= (1 - \xi) p_t \end{aligned}$$

For a firm, the probability that a vacancy will lead to a match is:

$$q_t^m = \frac{\bar{m}_t}{\bar{v}_t}$$

Now, not all matches will lead to hires since I assume that workers in bad matches accept only good jobs. Thus, the probability that a vacancy leads to a good quality hire (q_t^g) or to a bad quality hire (q_t^b) is given by

$$\begin{aligned} q_t^g &= \zeta q_t^m \\ q_t^b &= (1 - \zeta) \left(1 - \frac{\sigma \zeta_{bt} \bar{b}_t}{\bar{s}_t} \right) q_t^m \end{aligned}$$

Since all workers accept good matches, q_t^g is simply the product of the probability of a match being good conditional on a match and the probability of a match. However, since workers in bad matches do not make lateral movements, the fraction of searchers who search on-the-job from bad matches, $\frac{\sigma \zeta_{bt} \bar{b}_t}{\bar{s}_t}$ is netted out to calculate q_t^b . Thus, the expected number of workers in efficiency units of labor that a firm can expect to hire from posting a vacancy as:

$$q_t = q_t^g + \Phi q_t^b$$

Thus, the total number of new hires (in efficiency units) is $q_t v_t$ and the hiring rate χ_t is the ratio of new hires to the existing stock l_t , given by:

$$\chi_t = \frac{q_t v_t}{l_t}$$

We can now define some law of motions for the good and bad matches. respectively.

$$(18) \quad \bar{g}_{t+1} = \sigma \bar{g}_t + \xi p_t \bar{s}_t$$

$$(19) \quad \bar{b}_{t+1} = \sigma (1 - \zeta_{bt} (1 - \xi) p_t) \bar{b}_t + (1 - \xi) p_t \bar{u}_t$$

Total good matches next period are a sum of surviving good matches in the current period and an inflow of searchers into good matches, which depends on their probability of finding a good match. Similarly, total number of bad matches next period are a sum of two terms. the first term represents the number of workers in bad matches who are unable to find a good match and thus remain in the bad match. The second term is the number of unemployed workers who find bad matches and move into them. The current values of l_t , g_t and b_t are predetermined state variables.

The intra-period timing protocol that the firm's decision problem is based upon is: (i) realization of aggregate and firm-level shocks, (ii) wage bargaining and production, (iii) realization of match-level separation shocks, and (iv) search and matching. We can now look at the problems that the firms and workers face in the subsequent sub-sections.

Information Structure This section introduces an imperfect information structure which is analogous to the structural VAR deployed to recover the belief shocks as well as the persistent and transitory productivity shocks. The information structure aims to capture the fact that agents do not have full information about the state of the economy.

However, it is important to note that agents have rational expectations, given their information set. Agents do not perfectly know whether the current aggregate productivity, which is the only source of aggregate uncertainty, is persistent or transitory. They get a public signal about the persistent component and form expectations based on it. Let $z_t = \log Z_t$. From now on, a lowercase variable will denote the log of the corresponding uppercase variable. x_t is the permanent component and η_t is the temporary component.

$$(20) \quad z_t = x_t + \eta_t \quad ; \quad \eta_t \sim \mathcal{N}(0, \sigma_\eta^2)$$

x_t follows an AR(1) process:

$$(21) \quad x_t = \rho x_{t-1} + \epsilon_t \quad ; \quad \epsilon_t \sim \mathcal{N}(0, \sigma_\epsilon^2)$$

Each period, all agents in the economy observe a noisy signal \hat{s}_t about the permanent component of the productivity process, which is given by

$$(22) \quad \hat{s}_t = x_t + a_t$$

$$(23) \quad a_t = \rho_a a_{t-1} + v_t \quad ; \quad v_t \sim \mathcal{N}(0, \sigma_v^2)$$

The shocks η_t , ϵ_t and v_t are mutually independent. The noise term v_t in the signal a_t prevents the agents from perfectly identifying permanent innovations to technology and generates variation in the agents' beliefs regarding x_t , independent of the fundamentals. It is a pure shock to expectations and does not affect productivity. Permanent shock to productivity is ϵ_t which affects aggregate productivity and also affects beliefs. The temporary shock η_t affects agents' beliefs and realized productivity in the first period and only affects beliefs in the subsequent periods.

Persistence in Noise. Here, the noise is assumed to be persistent. This serves the purpose of making the signal extraction problem more complex for the agents. Agents now not only cannot discern if a shock is persistent, transitory or noise, but they also cannot discern whether the persistence in change in productivity is attributed to a true persistent change in productivity or a persistent signal.

Let $x_{t|t} \equiv x_t \mid \mathcal{I}^t$ denote the agents' expectations regarding x_t conditional on their information

set at date t . This implies, $x_{t|t} \equiv \mathbb{E}_t[x_t]$. Agents update their beliefs about x_t in a Bayesian manner, using a Kalman filter.

Thus, the dynamics of $x_{t|t}$ is.

$$(24) \quad x_{t|t} = \rho_x x_{t-1|t-1} + \mathbf{K}_{t-1}(\mathbf{s}_t - \mathbf{s}_{t|t-1})$$

where, \mathbf{s}_t is the vector of signals ($\mathbf{s}_t = [z_t, \hat{s}_t]$), and \mathbf{K}_t is the Kalman gain matrix. The details of the filtering process are in Appendix Section B.1.

Timing. Here, the timing of the signal and expectation formation is key, which is as follows:

1. Firms and workers form expectations at beginning of t with information set \mathcal{I}^{t-1} .
2. Firms and workers make their decisions for time period t .
3. Public signal is revealed as is the value of z_t . However, firms and workers do not learn from this signal in time period t (Pre-commitment).

Thus, agents make their decisions about time t outcomes based on the signal as well as the aggregate productivity they observed at the end of time period $t - 1$. Now, a key point to note here is that technically, the agents in the model could observe various real outcomes in the economy such as $z_t, y_t, c_t, u_t, v_t, s_t, w_t$ and learn about the true aggregate productivity. However, assuming that that signal extractions is costly and agents only use the signal to learn and make decisions. This assumption is similar to Woodford (2001), Mankiw and Reis (2002) and Angeletos et al. (2020) where agents do not learn endogenously.

Assumption 1 *Firms and workers observe publicly available real variables in the model at time t , but do not include them in their information set \mathcal{I}^t since this signal extraction is costly. Furthermore, all the information processing that the workers undertake to learn the state of the economy is summarized in the public signal a_{t-1} . Agents form their expectations at the beginning of the period before the signal is revealed for t and pre-commit to their decisions that they make in t , which are based on \mathcal{I}^{t-1} .¹¹*

Finally, under full information, the agents perfectly observe z_t and x_t each period. Thus, there is no information friction, and they immediately adjust their expectations.

Firm's Problem There is a continuum of firms indexed with a mass normalized to 1. All firms produce a homogeneous good that is sold in a competitive market. The aggregate productivity in the economy is z_t with a transitory component η_t and a permanent component x_t about which the agents receive a noisy public signal. Firms produce with capital and labor, and their output can be used for consumption or for capital accumulation. Capital is perfectly mobile and firms rent capital on a period by period basis. Firms add labor through a search and matching process

¹¹This assumption can be thought of as economic data releases being lagged by one period. Firms and workers see the data release in t , which contain the information from $t - 1$. This assumption tries to mimic this aspect. In the model, therefore, nowcast errors are analogous to the data nowcast errors.

described above. The production function is $y_t = z_t k_t^\zeta l_t^{1-\zeta}$. Let the stochastic discount factor be $\Lambda_{t,t+1}$, w_t be the wage per efficiency unit of labor and r_t be the capital rental rate. I assume that labor recruiting costs are convex in the hiring rate of labor in efficiency units, χ_t .

The firms decision problem is therefore to choose χ_t to maximize the value of the firms which is the discounted stream of profits net of recruiting costs, wages and capital rental expenses, subject to the law of motion for l_t , g_t and b_t , and given the expected paths of wages and rental rate. Firm's solve the following problem:

$$(25) \quad F_t = \max_{k_t, \chi_t} \mathbb{E}_t \left\{ z_t k_t^\zeta l_t^{1-\zeta} - \frac{\kappa}{(1+\eta_h)} \chi_t^{(1+\eta_h)} l_t - w_t l_t - r_t k_t + \Lambda_{t,t+1} F_{t+1} \mid \mathcal{I}^{t-1} \right\}$$

subject to the law of motions of l_t , g_t and b_t given in equations 17, 18 and 19. The first order conditions give us the rental rate of capital and a first order condition for hiring.

$$(26) \quad k_{t+1} : \quad z_t \zeta \left(\frac{l_t}{k_t} \right)^{1-\zeta} - r_t = 0$$

$$(27) \quad \chi_t : \quad -\kappa (\chi_t)^{\eta_h} l_t + \mathbb{E}_t (\Lambda_{t,t+1} F_{t+1}) = 0$$

Given Cobb-Douglas production technology and perfect mobility of capital, k_t does not vary across firms. It is also important to note that while the firm pays the same recruitment costs for bad and good workers (in quality adjusted units), bad workers have different survival rates within the firm due to their incentive to search on-the-job. The first order condition for hiring rate can be solved to get the vacancies v_t since $\chi_t = q_t v_t / l_t$. Each firm optimizes their hiring rate and in equilibrium, total vacancies are given by summing across all firms, $\bar{v} = \int_0^1 v_i di$.

Household's Problem There is a unit measure of families, each with a measure one of workers. The family pools all wage and unemployment income. Consumption and savings decisions are made at the household level, but household members make their decisions based on the same information set \mathcal{I} . Each family owns diversified stakes in firms that pay out profits and assigns consumption \bar{c}_t to members and saves in the form of capital \bar{k}_t , which is rented to firms at rate r_t and depreciates at the rate δ . The household solves the following problem,

$$(28) \quad \Omega_t = \max_{\bar{k}_{t+1}, \bar{c}_t} \mathbb{E}_t \left\{ \log(\bar{c}_t) + \beta \Omega_{t+1} \right\}$$

subject to

$$\begin{aligned} \bar{c}_t + \bar{k}_{t+1} + c(s_t^b) \bar{b}_t + c(s_t^u) \bar{u}_t &= \bar{w}_t \bar{n}_t + \phi \bar{w}_t \bar{b}_t + \bar{u}_t u_B + (1 - \delta + r_t) \bar{k}_t + T_t + \Pi_t \\ \bar{g}_{t+1} &= \sigma \bar{g}_t + \xi p_t \bar{s}_t \\ \bar{b}_{t+1} &= \sigma (1 - \zeta_{bt} (1 - \xi) p_t) \bar{b}_t + (1 - \xi) p_t \bar{u}_t \end{aligned}$$

Unemployed Workers Let U_t be the value of unemployment, V_t^g the value of a good match, and V_t^b the value of a bad match. u_B is the flow benefit from unemployment. An unemployed worker searches with an endogenous search intensity ζ_{ut} . The value of unemployment is given by:

$$(29) \quad U_t = \max_{\zeta_t^u} \mathbb{E}_t \left\{ u_b - c(\zeta_{ut}) + \Lambda_{t,t+1} \left((1-p_t)\zeta_{ut}U_{t+1} + \zeta_{ut}(1-\xi)p_t V_{t+1}^b + \zeta_{ut}\xi p_t V_{t+1}^g \right) \middle| \mathcal{I}^{t-1} \right\}$$

Here, in the current period, an unemployed worker receives u_b , net of search costs. In $t+1$, With probability $(1-p_t)\zeta_{ut}$, an unemployed worker does not find a job and remains unemployed in $t+1$.¹² Unemployed workers find it optimal to accept either a bad or a good match if they receive one if the wages are greater than their outside option.

Employed Workers Employed workers earn a wage w_j while employed at firm j . The workers in a bad match search on the job with endogenous intensity σ_{bt} and are matched with another firm with probability $\sigma_{bt}p_t$. However, I assume that employed workers only move up the ladder. They switch jobs only if they find a firm that offers a better continuation value. Employed workers are separated from their job with exogenous probability $(1-\sigma)$, in which case they have to spend at least one period in unemployment before they can be matched with another firm. The employed worker solves the following problem

Value of being employed for a worker in a good match is given by the following

$$(30) \quad V_t^g = \mathbb{E}_t \left\{ w_{gt} + \Lambda_{t,t+1} \left(\sigma V_{t+1}^g + (1-\sigma)U_{t+1} \right) \middle| \mathcal{I}^{t-1} \right\}$$

A worker in a good match earns wage w_{gt} while employed in a good match. Since there is no ladder to move up, these workers do not search on-the-job. In the next period, the worker can either get the separation shock in which case she flows into unemployment. Otherwise they continue being in a good match in the subsequent period.

Now, the value of being employed for a worker in a bad match is given by:

$$(31) \quad V_t^b = \max_{\zeta_{bt}} \mathbb{E}_t \left\{ \phi w_t - \sigma c(\zeta_{bt}) + \Lambda_{t,t+1} \left(\sigma \zeta_{bt}(1-\xi)p_t V_{t+1}^b + \sigma \zeta_{bt}\xi p_t V_{t+1}^g + (1-\sigma)U_{t+1} \right) \middle| \mathcal{I}^{t-1} \right\}$$

A worker in a bad match searches on-the-job and hence chooses their search intensity to optimize their value from a bad match. While in a bad match, the worker earns the wage w_{bt} , and if the worker survives within the firm, which occurs with probability σ , she searches with variable intensity ζ_{bt} , and since search is costly, they pay the cost of searching. In the next period, if they

¹²The average value of employment in the continuation value of U_t should be that of a new hire rather than the unconditional one. However, Gertler and Trigari (2009) show that the two are identical up to a first order.

are hit by the separation shock they flow into unemployment. If they remain employed in the bad match, the worker might be matched with a good job in which case they move to the good job next period. If matched with another bad match, the worker chooses to stay in the current bad job.

Wage Contracts Workers and firms divide the joint match surplus via staggered Nash bargaining à la Gertler and Trigari (2009). The firm bargains with workers in good matches for a wage while workers in bad matches then receive the fraction of the wage for good workers, corresponding to their relative productivity.¹³ Thus, when bargaining with good workers, firms also take account of the implied costs of hiring bad workers. For the firm, the relevant surplus per worker is:

$$J_t = \frac{F_t}{l_t}$$

For good workers, the relevant surplus is the difference between the value of a good match and unemployment:

$$H_t = V_t^G - U_t$$

The expected duration of a wage contract is exogenous. At each period, a firm faces a fixed probability $1 - \lambda$ of renegotiating the wage and with λ probability, the wage from the previous period is retained. The expected duration of a wage contract is $\frac{1}{1-\lambda}$. Workers hired in between contracting periods receive the prevailing firm wage per unit of labor quality w_t . The wage w_t^N is chosen to maximize:

$$(32) \quad w_t^N = \arg \max_{w_t} \left\{ H_t(w_t)^\eta J_t(w_t)^{(1-\eta)} \mid \mathcal{I}^{t-1} \right\}$$

subject to

$$(33) \quad w_{t+1} = \begin{cases} w_t & \text{with probability } \lambda \\ w_{t+1}^N & \text{with probability } 1 - \lambda \end{cases}$$

where w_{t+1}^N is the wage chosen in the next period if there is renegotiation and η is the households relative bargaining power. Now, to a first order approximation, the evolution of average wages can be written as follows

$$(34) \quad \bar{w}_t = (1 - \lambda) \bar{w}_t^N + \lambda \bar{w}_{t-1}$$

Here, the average wages and the average contract wage are defined by

$$\begin{aligned} \bar{w}_t &= \int_{w, \gamma} w dG_t(w, \gamma) \\ \bar{w}_t^N &= \int_{w, \gamma} w_t^N(\gamma) dG_t(w, \gamma) \end{aligned}$$

¹³This wage rule for workers in bad matches approximates the optimum wage from direct bargaining.

$dG_t(w, \gamma)$ denotes the time t fraction of units of labor quality employed at firms with wage less than or equal to w and ratio of bad-to-good workers less than or equal to γ .¹⁴

Resource Constraint To close the model, the resource constraint states that the total resource allocation towards consumption, investment, vacancy posting costs, and search costs is equal to aggregate output

$$(35) \quad \bar{y}_t = \bar{c}_t + \bar{k}_{t+1} - (1 - \delta)\bar{k}_t + \frac{\kappa}{2} \int_i \varkappa_t^2 l_t di + c(s_t^b)\bar{b}_t + c(s_t^u)\bar{u}_t$$

The government funds unemployment benefits through lump-sum transfers:

$$(36) \quad T_t + (1 - \bar{n}_t - \bar{b}_t)b = 0$$

Equilibrium The aggregate state of the economy is defined by $\Omega = \{l, g, b, k, z, x^T, n^T\}$. A recursive equilibrium is characterized as a solution for a set of (i) value functions $\{J_t, V_t^g, V_t^b, U_t\}$, (ii) prices $\{r_t, w_t^N, w_{t+1}, \bar{w}_t, \bar{w}_t^N\}$, (iii) allocations $\{\chi_t, \zeta_{ut}, \zeta_{bt}, \bar{k}_{t+1}, \bar{c}_t, \bar{g}_t, \bar{g}_t\}$, (iv) the density function of composition and wages across workers dG_t , a transition function $Q_t, t+1$, a law of motion for the economy Π_t , such that given the law of motion for exogenous variables z_t, x_t and n_t :

1. households optimize such that c_t, k_{t+1} satisfy the optimality conditions;
2. optimal search and hiring: $\zeta_{bt}, \zeta_{ut}, \chi_t$ optimize the Bellman equations for V_t^b, U_t, J_t ;
3. wage w_t^N satisfies the Nash Bargaining Rule and w_{t+1} is given by 34;
4. all Markets Clear: Rental market of Capital clears, households optimize consumption and search intensities. Firms optimize on hiring decisions and capital investment;
5. \bar{g}_t and \bar{b}_t evolve according to their respective laws of motion and the evolution of G_t is consistent with the transition function $Q_{t,t+1}$;
6. at each point in time, agents' beliefs are determined by their information set \mathcal{I}^{t-1} , their perceived law of motion for the economy. Agents update their beliefs about the aggregate productivity in a Bayesian manner with the timing consistent with Assumption 1.

5 Parameterization and Estimation

I estimate the parameters in the model at a quarterly frequency using a three-step procedure. First, I fix the parameters $\{\beta, \delta, \zeta, \omega, \gamma, \lambda, \alpha, \eta_h, \rho_z\}$ to widely accepted values from the literature.

¹⁴Under multi-period bargaining, the outcome depends on how the new wage settlement affects the relative surpluses of firms and workers in subsequent periods where the contract is expected to remain in effect. As shown in Gertler and Trigari (2009), up to a first order approximation, the contract wage will be an expected distributed lead of the target wages that would arise under period-by-period Nash bargaining, where the weights on the target for period $t+i$ depend on the likelihood the contract remains operative which is λ^i .

Table 3: Parameter Values

Parameters	Interpretation	Value	Source
β	Discount rate	0.99	Shimer (2005)
δ	Depreciation rate	0.025	Gertler and Trigari (2009)
ζ	Production function parameter	0.33	Gertler et al. (2020)
ω	Elasticity of search cost	3.60	Faberman et al. (2022)
γ	Worker's bargaining power	0.5	Shimer (2005)
λ	Renegotiation frequency	0.75	Gertler et al. (2020)
α	Elasticity of matches to searchers	0.4	Blanchard and Diamond (1989)
η_h	Hiring cost convexity	2.40	Merz and Yashiv (2007)
ρ_z	Technology autoregressive parameter	0.949	Shimer (2005)

Note: This table reports the parameter values that have been fixed to widely accepted external values in the literature.

Then, I estimate $\{\Psi, \kappa, \mu, \sigma, \phi, u_b, \xi\}$ by targeting some unconditional stationary moments using the simulated method of moments. Finally, the remaining parameters $\{\sigma_\epsilon, \sigma_n u, \rho_n, \mathcal{K}\}$ are estimated to match the impulse responses of unemployment rate, vacancies, outflow from unemployment, job-to-job transition rates, hiring rates and wage growth to the identified noise shocks as well as the persistent productivity shock in the data. Table 3 summarizes the result of the calibration strategy. I calibrate the output elasticity of labor $\alpha = 0.33$, the discount factor $\beta = 0.99$, and depreciation rate $\delta = 0.025$ to widely accepted values in the literature.

Targeting Unconditional Moments. As a first step, I target the steady state unemployment rate, unemployment-to-employment transitions, job-to-job transitions and separation rate in the model to match the average values from the United States for the period 1968-2019. I also target the flow value of unemployment, u_B , to match the relative value of non-work to work activity $\bar{u}_T = 0.71$ following Hall and Milgrom (2008).¹⁵

The efficiency parameter Ψ is targeted such that the steady state unemployment rate in the model matches the average unemployment rate from 1968-2019 in the data, and takes a value of 0.49. The hiring cost parameter κ determines the resources that firms invest into recruiting, and hence, influences the probability that a worker finds a job. I set the steady state job finding probability to match the quarterly U-E transition probability, $\tilde{p} = 0.28$; and then calibrate κ to be consistent with \tilde{p} . Furthermore, a higher search cost implies a lower E-E probability and hence, the search cost parameter μ is targeted to match E-E probability, and takes a value $\mu = 0.082$. The separation rate σ is targeted to match the E-U probability. The steady state productivity from a bad job, ϕ is targeted to match the change in wage of workers who make job-to-job transitions. The ratio of bad jobs to good jobs is held constant and is calibrated following Gertler et al. (2020).¹⁶ I further

¹⁵The relative non-work to work satisfies EXPRESSION. The value of non-work includes saved search costs from on-the-job search and the value of work includes saved vacancy posting costs.

¹⁶

$$\frac{\bar{b}}{\bar{g}} = \frac{(1-\lambda)(p^{EE} + p^{EU})}{p^{EE} + \lambda p^{EU}}$$

Table 4: Unconditional Targeted Moments

Parameters	Interpretation	Value	Target
Ψ	Match efficiency	0.49	Unemployment Rate = 0.055
κ	Cost of hiring	7.21	$U - E = 0.28$
μ	Scale parameter of search cost	0.082	$E - E = 0.025$
$1 - \sigma$	Separation rate	0.010	$E - U = 0.010$
ϕ	SS productivity from bad job	0.76	Average E-E wage increase = 0.045
ξ	Probability of finding a good job	0.24	Average wage-improv. flow share = 0.53
u_b	Flow value of unemployment	2.43	Relative value, non work = 0.71

Note: This table reports the parameters estimated using Simulated Method of Moments to target some key stationary moments in the data. These moments are: unemployment rate, unemployment to employment transition rate, job-to-job transition rate, employment to unemployment separation rate and wage change of workers who make job to job transitions. These moments are calculated over the sample period 1968q4 - 2019q4 using the CPS.

calibrate ζ to match the average share of job transitions involving positive wage changes out of total job flows and target this number to be 0.527, following Gertler et al. (2020). The corresponding value if $\zeta = 0.23$. A lower probability of finding a good job corresponds to a higher steady state value of bad-to-good workers, and hence a higher average share of bad-to-good flows. Finally, the hiring cost convexity η_h is targeted to match

Impulse Response Matching. I estimate the remaining model parameters by matching model-implied responses following a noise shock, and TFP shock to their counterparts in the empirical exercise (Rotemberg and Woodford, 1997; Christiano et al., 2005). The targets are the responses of unemployment rate, U-E rate and E-E rate for horizons of up to 20 quarters.¹⁷ The impulse response matching is done by minimizing the distance between the model-generated impulse response functions (IRFs) and the empirical IRFs. Let f_i be the column vector stacking the point estimates of each of these impulse responses, where $i = 1, \dots, N$ indexes the different IRFs, and h is the horizon at which the IRFs are being evaluated. The model-generated IRFs are denoted as $f_m(\Theta)$, where Θ is a vector of model parameters. The optimization problem is given as:

$$(37) \quad \min_{\Theta} (f - f_m(\Theta))' W (f - f_m(\Theta))$$

where, $\Theta = \sigma_e^2, \sigma_v^2, \rho_n, \mathcal{K}$, where \mathcal{K} is the signal-to-noise ratio. The weight matrix W is the inverse of the variance-covariance matrix of the empirical IRF estimates.¹⁸

The result of this estimation process is documented in Table 5, with standard errors calculated using the delta method (Guerron-Quintana et al., 2017). The signal-to-noise ratio is 0.23, which is low as the noise shocks have a large variance. Thus, the implied standard deviation of the transitory

where p^{EE} and p^{EU} are probability of E-E transitions and E-U transitions respectively

¹⁷Thus, we have 6 impulse responses in total for this matching exercise.

¹⁸The objective function becomes a form of the generalized method of moments estimator. In this case, the optimization problem aims to match moments (the IRFs) in a way that is efficient given the variability of the empirical estimates.

Table 5: Estimated Parameters from IRF Matching

Parameters	Interpretation	Estimate	Std. Error
σ_ϵ	Std. Dev of Persistent TFP shock	0.062	0.009
σ_v	Std. Dev of Noise Shock	0.096	0.007
ρ_n	Noise autoregressive parameter	0.921	0.004
K	Signal-to-Noise Ratio	0.023	0.003

Note: This table reports the estimated parameters from the impulse response matching exercise outlined in equation 37. The third column reports the estimated values while the fourth column reports the standard errors for these values. The impulse responses are matched by GMM and the standard errors are calculated using the delta method.

productivity shock is found to be $\sigma_\eta = 0.192$, which is relatively large compared to the standard deviation of the noise shock as well as that of the persistent TFP shock, so that learning about the persistent component of productivity is gradual. This implies that the agents in the economy learn quite slowly about the true persistent TFP component.

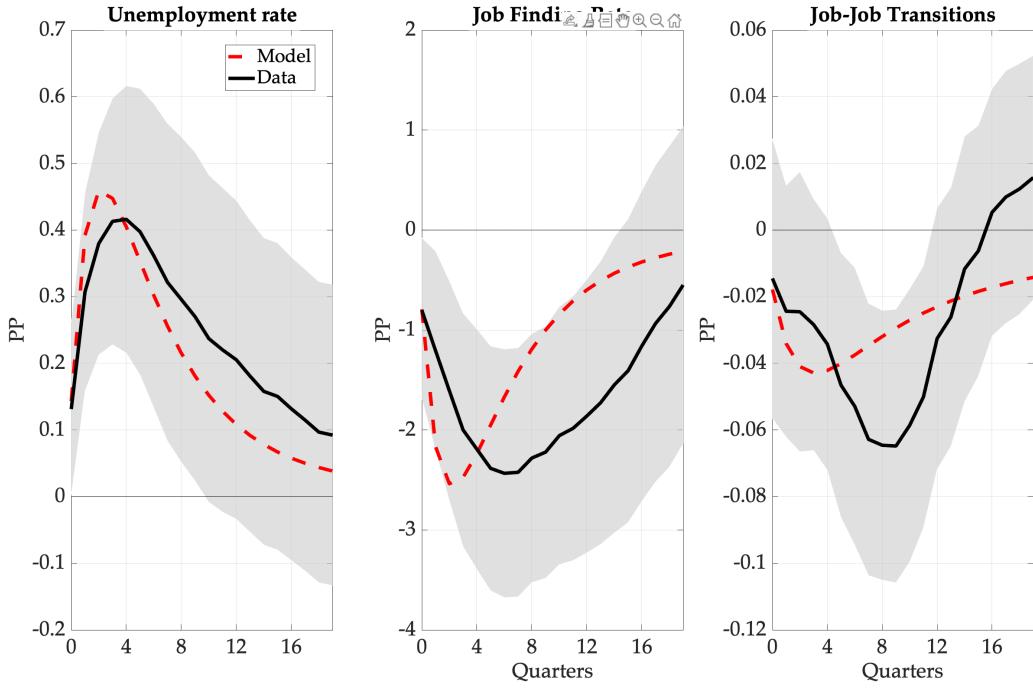
Figures 6 plots the impulse responses from the empirical exercise and the impulse responses implied by the estimated model in response to a noise shock and a persistent TFP shock. The model fit is good, with all the model implied impulse responses falling within the confidence bands from the empirical exercise. The impact as well as the dynamics for unemployment rate, job finding rate and job-to-job transitions matches the empirical impulse responses well. The dynamics for vacancies and hiring rate are not matched well as the model fails to capture the curvature which the empirical impulse responses display.

The benchmark model for the rest of the paper is the imperfect information model with noise shocks. I consider several counterfactual models. The first is the full information model which is re-calibrated as discussed in Appendix Section B.2. In this framework, firms and workers perfectly observe z_t, x_t every period and immediately revise their expectations. The second framework, is the imperfect information model without noise shocks. This model is not re-calibrated. Here, firms and workers still have imperfect information and do not observe x_t , but only see the signal \hat{s}_t each period. However, the noise shocks are never realized. This model serves as an important comparison to highlight the role of imperfect information.

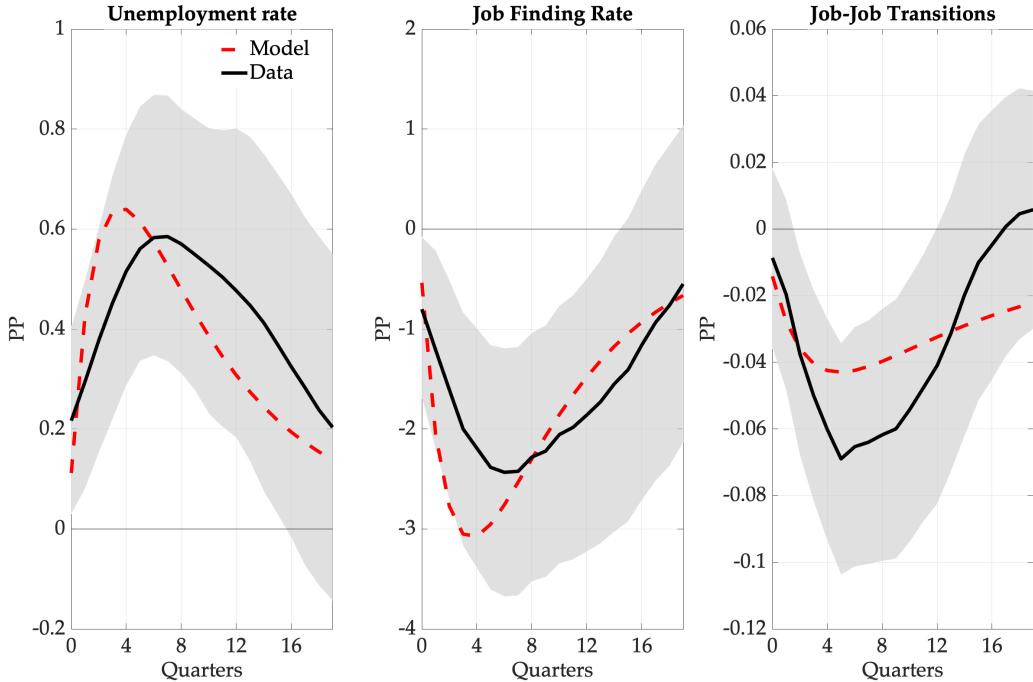
Business Cycle Statistics To understand how the model with imperfect information performs with respect to the observed business cycle statistics in the data, I report the volatility and correlation of several labor market outcomes with output in Table 6. The table compares the business cycle statistics obtained by simulating the benchmark model and the full information model, to the statistics in the US economy from 1968-2019 for unemployment rate (U), job vacancies (V), job-to-job transitions (EE), job transitions from unemployment to employment (UE), and hiring rate.

While both models offer reasonable approximations of output data, the imperfect information model outperforms the full-information model across all other variables, both in terms of standard deviation and correlation with output and is closer to empirical observations. It's worth acknowledging that the full-information model already incorporates features like wage rigidity

Figure 6: Impulse Responses from Data and Estimated Model



(a) Noise Shocks



(b) Persistent TFP Shock

Note: This figure plots the results of IRF matching for noise shocks and persistent TFP shocks.

Table 6: Business Cycle Statistics

x	Data		Full Information		Imperfect Information	
	(1) SD	(2) $\text{corr}(Y, x)$	(3) SD	(4) $\text{corr}(Y, x)$	(5) SD	(6) $\text{corr}(Y, x)$
Y	0.019	1	0.019	1	0.027	1
U	0.162	-0.859	0.010	-0.754	0.148	-0.785
V	0.182	0.702	0.131	0.680	0.193	0.718
$E - E$	0.102	0.720	0.069	0.649	0.086	0.881
$U - E$	0.069	0.734	0.048	0.589	0.077	0.686
Hiring Rate	0.058	0.677	0.033	0.599	0.049	0.743

Note: This table reports standard deviation of key labor market variables and their correlation with output in the model. The data here has been simulated from the model and HP-filtered (100,00).

and on-the-job search—factors known to induce volatility in search models (Shimer, 2005). Yet, the introduction of imperfect information augments the volatility of unemployment by an additional 23% relative to the full-information benchmark. Similarly, the imperfect information framework yields higher volatility for job vacancies and transition rates. This underscores the imperfect information model’s enhanced efficacy in capturing the dynamics of labor markets.

Forecast Error Variance Decomposition The identified noise shocks explain about a third of the variance in the labor market at a short run horizon. To understand how the benchmark model compares to the observed moments, I report the forecast error variance decomposition calculated by simulating the imperfect information model, in Table 7, for 8 quarters. The benchmark model can match the forecast error variances of the key labor market outcomes observed in the data reasonably well. The model predicts that the noise shocks explain 31% of the forecast error variance in unemployment rate which is 90% of the forecast error variance in the data explained by noise shocks. On average, the model overpredicts the forecast error variance by 7%.

Table 7: FEVD: Data and Model

	Data			Model		
	Horizon: 0-8 quarters			Horizon: 0-8 quarters		
	Persistent	Transitory	Noise	Persistent	Transitory	Noise
Unemployment	0.41	0.23	0.34	0.48	0.21	0.31
Vacancies	0.42	0.21	0.37	0.49	0.19	0.32
Job-finding Rate	0.38	0.27	0.35	0.42	0.21	0.37
E-E	0.42	0.31	0.27	0.49	0.17	0.34
Wages	0.61	0.25	0.14	0.60	0.22	0.18

Note: This table reports the forecast error variance in the model with imperfect information and compares it to the moments in the data.

6 Role of Imperfect Information in Labor Market Dynamics

The benchmark model with information frictions is not only a good fit to the data, as seen in the previous section, but also predicts higher volatility in the labor market than the model with full information. Now, the identified noise shocks played an important role in explaining the slow recovery of unemployed in the data. In this section, I first explain a propagation mechanism of shocks under imperfect information in the benchmark model. After establishing the mechanism, I document a counterfactual exercise to demonstrate that imperfect information can contribute significantly to the slow recovery of unemployment rate in recessions. Finally discuss the importance of various other channels such as sticky wages and on-the-job search, which have been proposed as possible channels for generating higher persistence in search and matching models.

6.1 Mechanism for Propagation of Shocks under Imperfect Information

Figure 7 illustrates the effect of a one standard deviation negative persistent productivity shock on key outcomes. The solid lines represent the imperfect information framework, while the dashed lines are the full information benchmark. In an environment characterized by imperfect information, agents—both firms and workers—operate under a Bayesian learning framework where they assign probabilistic weights to shocks as either persistent, transitory, or mere noise.

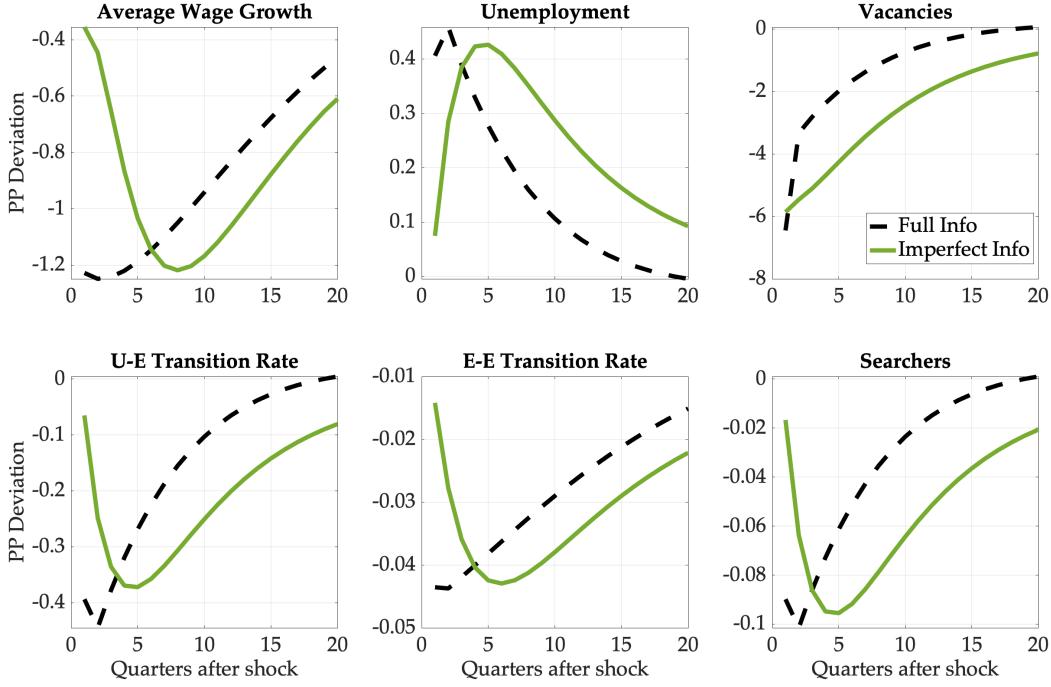
The uncertainty surrounding the nature of these shocks induces a form of temporal inertia in agent responses. Due to sticky wages, firms and workers do not immediately adjust wages as much as in the full information benchmark. This initial under-reaction stems from the risk that if the shocks are transitory or merely noise, an increase in wages would be sub-optimal when subsequently productivity levels decline, thereby reducing the future discounted profits.

In contrast to a full-information benchmark where responses are immediate and unambiguous, under imperfect information, we observe a moderated initial decrease in key labor market variables such as job vacancies, job-to-job transitions, and *UE* transitions. Consequently, unemployment rises, albeit less than the full-information benchmark.

As agents update their beliefs over time, incorporating more data and leaning towards the possibility of the shock being persistent, we see a more pronounced adjustment mechanism. As the firms and workers put more weight on the shock being persistent, the firms that get a chance to renegotiate, decrease wages, as their expected future discounted revenue declines. Concurrently, the labor market experiences dual pressures on vacancy postings: initially, the reduction in wages enhances firms' labor demand, offsetting the decline in productivity to some extent.

However, as firms update their beliefs about a persistent downturn in productivity, this labor demand attenuates. Equilibrium dynamics reveal a nuanced impulse response: vacancies experience an additional dip before gradually rebounding, signaling that the wage adjustments fully counterbalance productivity declines only after sufficient wage depreciation has occurred. This triggers decrease in search intensity and job-to-job transition rates, as workers now anticipate lower wages and thus lower surplus from a match. Firms post fewer vacancies as they now place

Figure 7: Impulse Response to a Positive Persistent TFP Shock



Note: This figure plots the impulse response functions for the re-calibrated full information model (dashed black line) and the imperfect information model (solid green line) to a negative 1 standard deviation persistent TFP shock.

higher weight on the shock being a true negative persistent shock. Consequently, unemployment starts increasing in a hump-shaped trajectory.

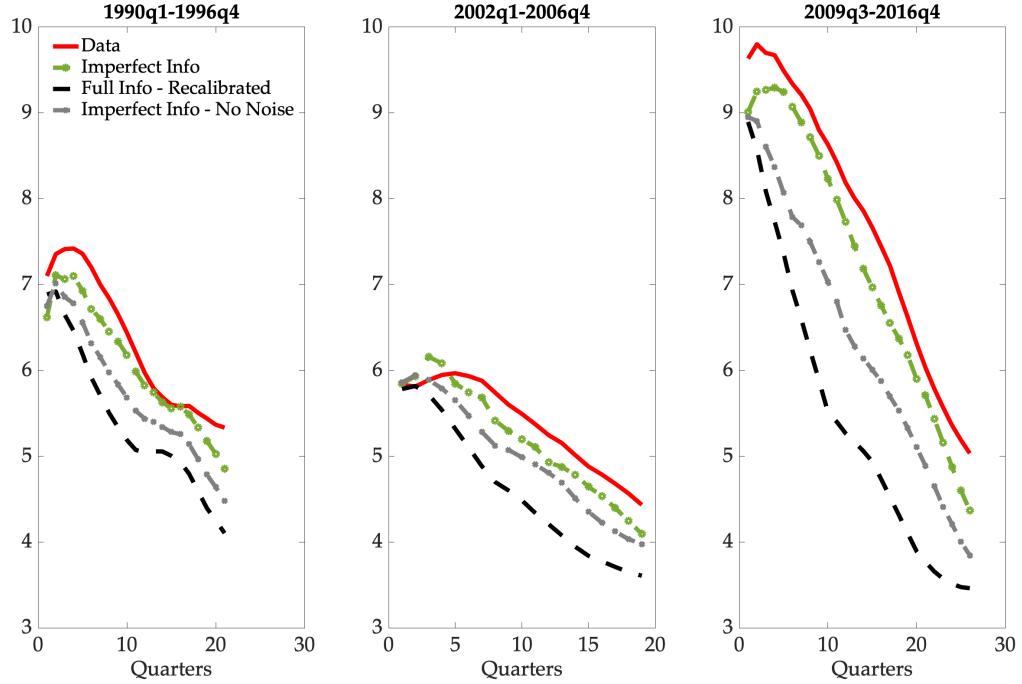
This illustrates the importance of sticky wages in propagating the imperfect information. If wages were flexible, they could keep adjust immediately as agents learn about the nature of the shock, and recovery would be faster.

6.2 Unemployment Dynamics across Recessions: Data vs Model

The calibrated model is simulated to generate counterfactual unemployment rate series for 5 recessions between 1970-2019. This exercise shows that imperfect information explains the slow recovery of unemployment rate in the last three recessions. For this exercise, the model is normalized to match the starting unemployment rate for each of the recessions. While simulating the imperfect information model, each period, all three identified shocks from the VAR are incorporated. For the full information model, I only introduce the persistent and the transitory shocks each period. Furthermore, the full information model is re-estimated as described in the previous section, to match the empirical IRFs to the persistent TFP shocks. The estimated parameters for the full information model is presented in the Appendix.

The imperfect information model predicts the persistence of the unemployment rate for the three recessions post 1990 quite well. On the other hand, the full information model recovers

Figure 8: Model Implied Recovery of Unemployment for Recessions Post 1990s



Note: This figure plots the model implied, simulated unemployment rate for the re-calibrated full information model (dashed blue line), the imperfect information model without noise (gray line) and the imperfect information model (solid green line) for the Great Recession, 2001 recession and the 1990-91 recession.

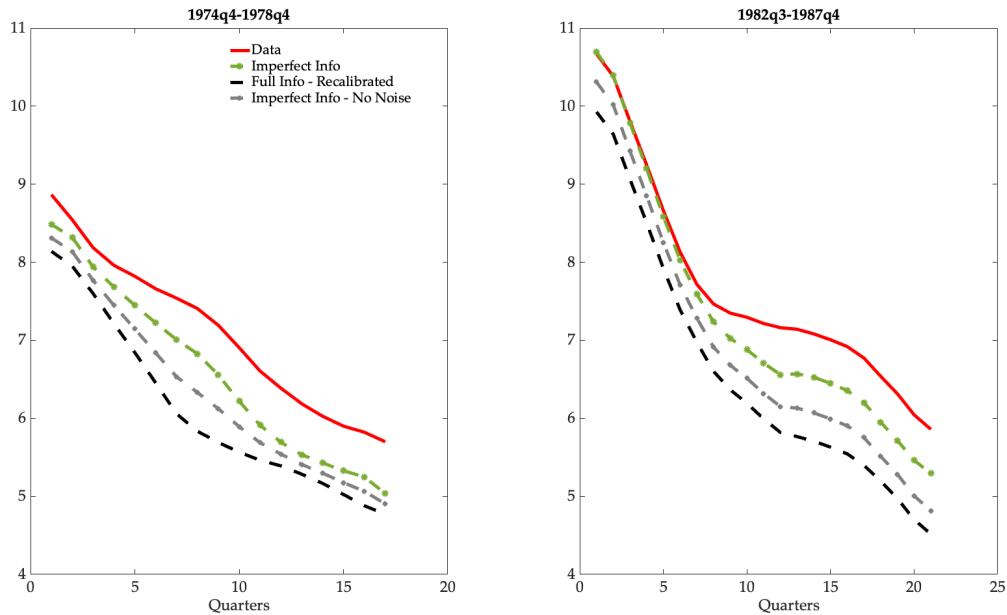
much faster for all three recessions. For the great recession, the actual unemployment rate took 37 quarters to recover to its pre-recession trough. The imperfect information predicts the recovery at 32 quarters whereas the full information model predicts a much faster recovery at 24 quarters. In other words, the imperfect information model predicts almost 33% slower recovery than the full information benchmark.

For the 2001 recession, the duration of recovery for unemployment was 24 quarters, and the imperfect information model (20 quarters) predicts 25% slower recovery than the full information model (16 quarters). In 1991 recession, the unemployment recovery took 28 quarters. The imperfect information model predicted a recovery at 22 quarters, almost 38% higher than the full information benchmark which predicted recovery at 16 quarters. This highlights the contribution of imperfect information to the persistence of the labor market. Larger noise shocks further dampen the economy as firms and workers perceive a negative productivity shock to be more persistent than it actually is. The slow learning by agents combined with sticky wages, translates into a slower recovery.

For the pre-90s recessions, both the models are comparable in their prediction for recovery of unemployment rate. This is because the noise shocks identified in the SVAR play a much smaller role in explaining the fluctuations in the labor market. With smaller noise shocks, the agents'

perceived productivity, while still lower than actual, was not too far off from the true productivity. Thus, the imperfect information model predicts similar recovery relative to the full information model. To be precise, in the 1981-82 recession (14 quarters), the imperfect information model predicts recovery in 11 quarters while the full information model predicts recovery in 9 quarters. For the 1973-78 recession (23 quarters), the imperfect information model predicts recovery in 17 quarters while the full information model predicts recovery in 14 quarters. The results are also summarized in Appendix Table B2.

Figure 9: Model Implied Recovery of Unemployment for Recessions Pre 1990s



Note: This figure plots the model implied, simulated unemployment rate for the re-calibrated full information model (dashed blue line), the imperfect information model without noise (gray line) and the imperfect information model (solid green line) for the Great Recession, 2001 recession and the 1990-91 recession.

6.2.1 Model Decomposition: Sticky Wages, On-the-job Search and Imperfect Information

In this section, I compare the persistence of unemployment under various mechanisms with and without imperfect information. In this model, there are three factors that add to the persistence of the unemployment rate: on-the-job search, sticky wages and learning. To understand the contribution of each channel, I compare a full information benchmark to imperfect information model under 4 scenarios: a) flexible wages without on-the-job search b) flexible wages with on-the-job search, c) sticky wages without on-the-job search, and d) sticky wages with on-the-job search.

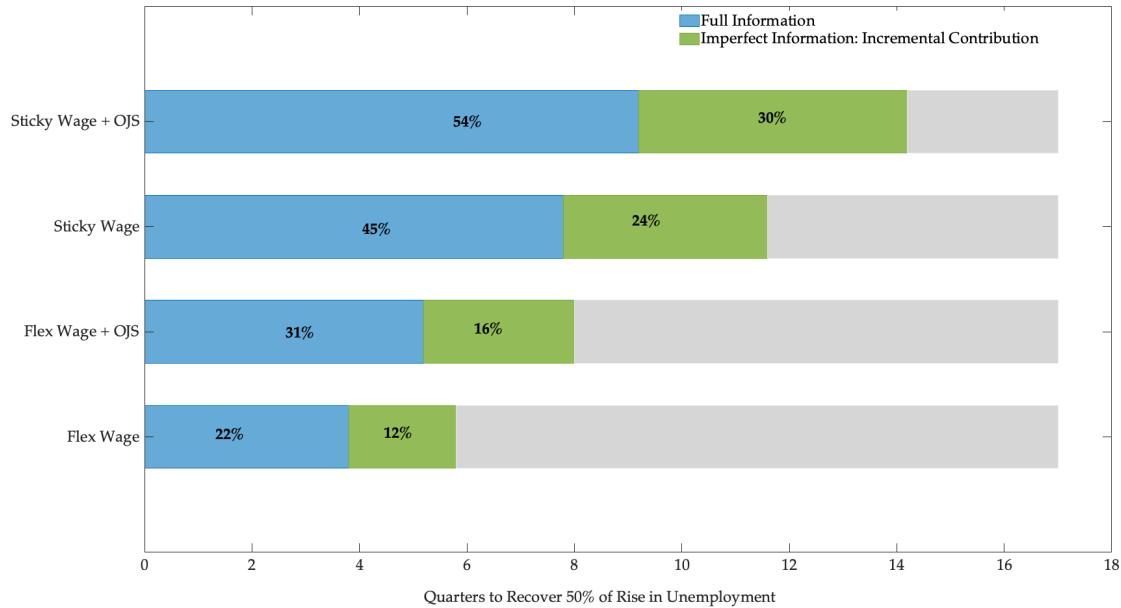
The measure of persistence I use is the average number of quarters across recessions to recover 50% of the rise in unemployment during recession. I calculate for each recession between

1968-2019, the share of the rise in unemployment during the recession that has been reversed during the expansion (Heise et al., 2022)

$$u_{recovery,t} = \frac{u_{peak} - u_t}{u_{peak} - u_{trough}}$$

For each recession, I calculate the average number of quarters it takes from the beginning of the recession to recover 50% of the rise in unemployment. Empirically, it took 17 quarters from the beginning of the recession to recover 50% of the rise in unemployment across recessions between 1968-2019. To highlight that learning contributes to persistence under each specification, I plot this measure in Figure 10. In the stacked bar graph, I re-calibrate the full information model as discussed in Section B.2.

Figure 10: Average Duration to Recover 50% of Rise in Unemployment Across Models



Note: This figure plots the model implied duration to recover 50% of the rise in unemployment from the beginning of the recession, averaged across recessions between 1968-2019 for various model specification. The percentages are the percent of the data (18 quarters) that the particular model specification explains, while the x-axis is the actual number of quarters explained by the particular specification. The green bars are incremental contributions by learning, which implies that the total contribution of the imperfect information model is the sum of the blue and the green bar. Here, the full information model is re-calibrated as discussed in Section B.2. Further, I shut down each mechanism one by one in both models.

Role of sticky wages. Sticky wages generate persistence in the labor market by making wage adjustment sluggish. As wages are slower to adjust downwards during recessions, incentive for firms to hire workers remains low. Thus, hiring declines and results in a lower job-finding rate with higher unemployment for longer than if the wages were flexible to adjust. Introduction of sticky

wages with no on-the-job search contributes significantly to the persistence of unemployment, and under full information, it accounts for 45% (7 quarters) of the 50% of the rise in unemployment.

Role of on-the-job search. During downturns, on-the-job search creates congestion for the unemployed workers as the pool of employed workers in bad matches increases. This is because the incentive for employed workers to move up the ladder is low due to lower productivity. And as the probability of finding a good job is exogenously low, unemployed workers have lower vacant bad jobs to move into and thus, finding a job takes longer, creating persistence in the unemployment rate. When on-the-job search is introduced to a flex wage full information model, it predicts about 30% (5 quarters) of the duration to recover 50% of the rise in unemployment rate. When on the job search interacts with sticky wages, the full information model predicts about 54% (9 quarters) of the persistence observed in the data.

Role of imperfect information. The previous two paragraphs highlighted that both on-the-job search and sticky wages endogenously generate persistence, predicting the unemployment rate to recover 50% of its rise in 10 quarters. To understand how much does imperfect information add to the persistence, we must look at the contribution coming from learning across all the model specifications. During downturns, due to noise shocks, firms and workers perceive the aggregate productivity shocks to be more persistent than they are. Since they only learn over multiple periods whether a shock is persistent or transitory, this generates a sluggishness as they keep behaving as if facing a negative productivity shock which is more persistent than the true shock. Firms anticipate lower returns from hiring while workers decline their search effort, leading to lower number of matches for as long as they learn about the true shock. When introducing imperfect information to the flexible wages without on-the-job search framework, persistence increases, predicting the unemployment to recover 50% of its rise in 6 quarters (35% of the total duration).

Learning interacts with on-the-job search and generates an additional 16% to the persistence of unemployment, predicting the 50% of the recovery in 8 quarters. Here, the employed workers are learning slowly about the true shock and they anticipate the productivity to be persistently worse than actual. As a result, movement up the job ladder remains damped for longer, therefore taking longer for unemployed workers to find jobs. This leads to damped job finding rates for longer and hence higher duration of recovery of unemployment rate.

Learning interacts with sticky wages and generates higher persistence even without on-the-job search. Firms anticipate the productivity to be persistently worse than actual, which decreases their incentives to hire which is further amplified by wages which are slow to adjust downwards. Therefore, hiring remains damped as they slowly learn about the true shock. Workers also decrease search effort and combined with lower hiring, this leads to damped job finding rates and hence unemployment rate takes much longer to recover. Imperfect information with sticky wages predict that it would take 11 quarters to recover the 50% of the rise in unemployment. This is 65% of the recovery duration in the data and is 24% higher than the full information sticky wage

model.

Finally, I show that imperfect information with sticky wages and on-the-job search adds a substantial 5.5 quarters (30%) to the average duration to recover 50% of the rise in unemployment, as compared to the full information counterpart. In equilibrium, as firms and workers anticipate the productivity to be persistently lower than actual due to imperfect information, sticky wages decline the incentives to hire even further, while decline in on-the-job search makes it harder for unemployed workers to find jobs, thus endogenously generating 84% of the persistence observed in the data.

In Appendix Section B.4.2, I discuss the model decomposition, comparing the full information model with the imperfect information model without noise shocks. This analyses establishes that learning endogenously leads to higher persistence of unemployment, even without noise shocks. In the model with sticky wages and on-the-job search, imperfect information adds 18% to the persistence of unemployment rate (approximately 3 quarters). This highlights the importance of incorporating imperfect information in models of search and matching to accurately predict the duration of recovery of unemployment from recessions.

6.2.2 Inclusion of COVID-19 recession

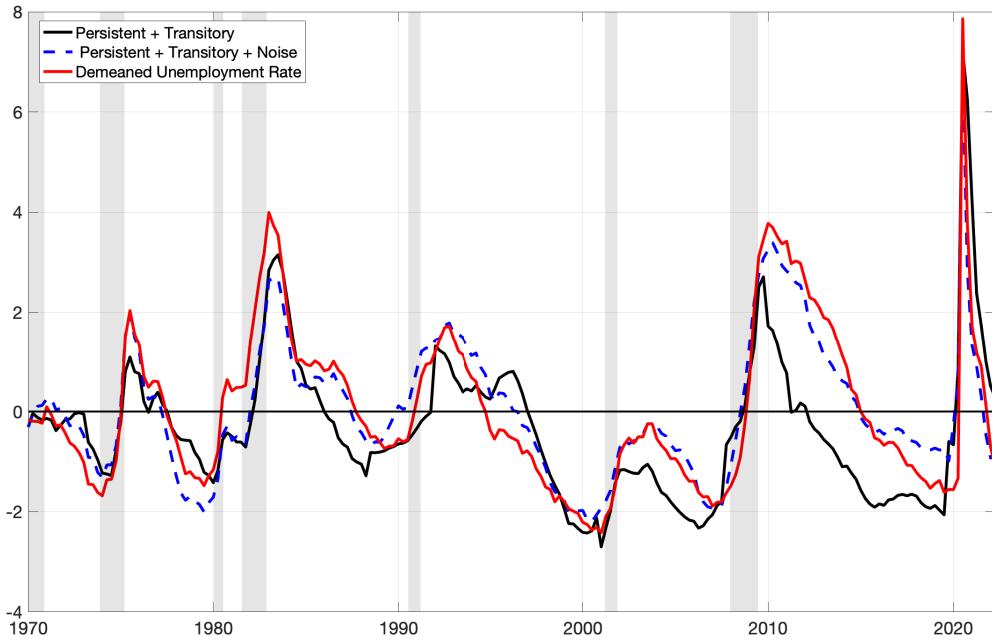
The Covid-19 recession in 2020 was a particularly shorter one and to understand the role of imperfect information, I extend the SVAR by including the Covid 19 pandemic in my sample (1968-2022). However, it is important to note that to identify the shocks in the Covid years, I have to assume that the persistent shock maximizes the forecast error variance of TFP even in the short run. However, since the identification of noise shocks does not depend on the max-share identification, this exercise is still informative about the dynamics of unemployment rate driven by noise shocks.

I plot the historical decomposition in Figure A13. The focus is however on noise shocks and it is evident that the noise shocks did not play an important role in this recession, as most of the fluctuation is picked up by the two TFP shocks. The reason might be because of the fact that in the short run, forecasters predicted a much transitory recovery.

7 Conclusion

This paper assess the role of imperfect information in labor market fluctuations and recovery patterns. Using a tri-variate structural VAR model, I identify noise shocks and their significant effects on labor market dynamics. I document that in the presence of imperfect information, noise shocks can be an important driver of the slow recovery of unemployment during recessions. Furthermore, noise shocks account for one-third of the variance in unemployment, job finding rate, and vacancy postings at the business cycle frequency. Through a counterfactual exercise, I find that without noise shocks, the labor market would have recovered faster by 7 quarter on average in the downturns between 1968-2019.

Figure 11: COVID-19: Historical Contribution of Shocks to Unemployment Rate



Note: This figure plots the historical decomposition of unemployment rate following equation 15. The black line is the cumulative contribution of the identified persistent and transitory TFP shocks to the movements in demeaned unemployment rate (red line). The dashed blue line is the contribution of the TFP shock and the noise shocks, which contribute significantly to the unemployment rate during the recessions in 1990-91, 2001 and 2007-09. The remaining movement here is explained by the 4th shock μ_t .

The introduction of imperfect information in a general equilibrium model provides a more robust framework for explaining the phenomena observed in the labor market. The model with imperfect information predicts 27% higher persistence in recovery of unemployment on average across recessions, relative to the standard model with full information. It also predicts 23% higher volatility in the labor market indicators. This is particularly true for the period after 1990, emphasizing the increased importance of imperfect information in more recent economic conditions.

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A Empirical Appendix

A.1 Data Sources

This subsection describes all the data sources used in this paper. The sample period for all the primary analysis is 1968q4 to 2019q4.

1. Unemployment rate and unemployment to employment transition rates are constructed from the Current Population Survey (CPS).
2. Since 1994, the CPS has asked individuals whether they still work at the same job as in the previous month. However, it is not possible to observe job-to-job transitions prior to 1994 and my sample changes to 1994-2019 for the job-to-job transitions.
3. Vacancies are measured as an index constructed based on the composite help-wanted index computed Barnichon (2010a), as it goes back to the beginning of my sample (1968).
4. Real GDP and wage (average hourly earnings) series are from BEA.
5. Aggregate productivity is measured as the Solow residual, for which I rely on the utility adjusted series from Fernald (2014), also updated by the Federal Reserve Bank of San Fransico.
6. Nowcast Errors: The GDP nowcast errors are constructed from the median forecast from the Survey of Professional Forecasters, which starts in 1968q4.

A.2 Recovery Pattern of the Labor Market

The labor market recovery has been sluggish and typically lags behind the recovery of output. Figure A1 illustrates the recovery pattern of unemployment and vacancies. In particular, the last three recessions before the pandemic have been slower. Specially the recessions occurring in 1990-91, 2001, and 2007-09, display distinct features from the postwar recoveries observed before the 1990s. In these recoveries, unemployment levels remained elevated, while both employment growth and job vacancies were sluggish for multiple quarters following the trough in output. I compute the duration to recover the rise in unemployment across various recessions. I calculate the following $u_{recovery}$ duration to recover 25%, 50%, 75% and 100% rise in unemployment across recessions. These are reported in Table A1

$$u_{recovery} = \frac{u^{peak} - u_t}{u^{peak} - u^{trough}}$$

A.3 Projections from Forecasters and Policymakers

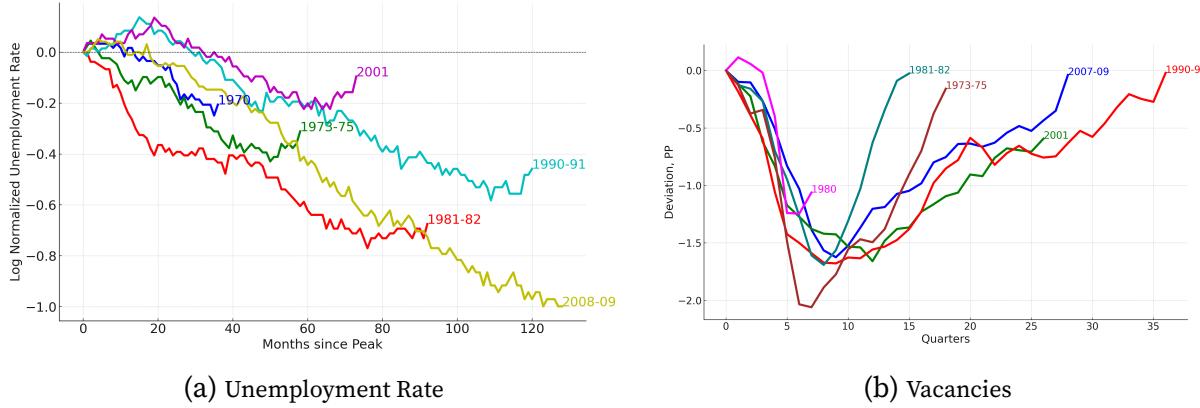
As noted in the introduction, the standard assumption in most macroeconomic model is that agents immediately recognize the nature of such a shock and adjust their expectations (and decisions). However, it can take agents much longer to learn about the true nature of the shock.

Table A1: Quarters Since the Peak to Recover the Rise in Unemployment Across Recessions

Recessions	(1) 25%	(2) 50%	(3) 75%	(4) 100%	(5) NBER Recovery
2007-09	9	16	21	33	25
2001	3	9	14	NA	40
1990-91	4	8	13	21	31
1981-82	4	5	15	22	4
1973-75	4	10	17	NA	12
1969-70	8	12	NA	NA	36
Average: Total	5	10	16	25	30
Average: Pre 2000	5	9	15	22	21
Average: Post 2000	6	13	18	33	33

Note: This table reports the number of quarters taken to recover the 25%, 50%, 70% and 100% of the rise in the unemployment rate from its peak, across recessions between 1968-2019, except the recession in 1980 which was quickly followed by the downturn in 1981-82.

Figure A1: Recoveries across Recessions

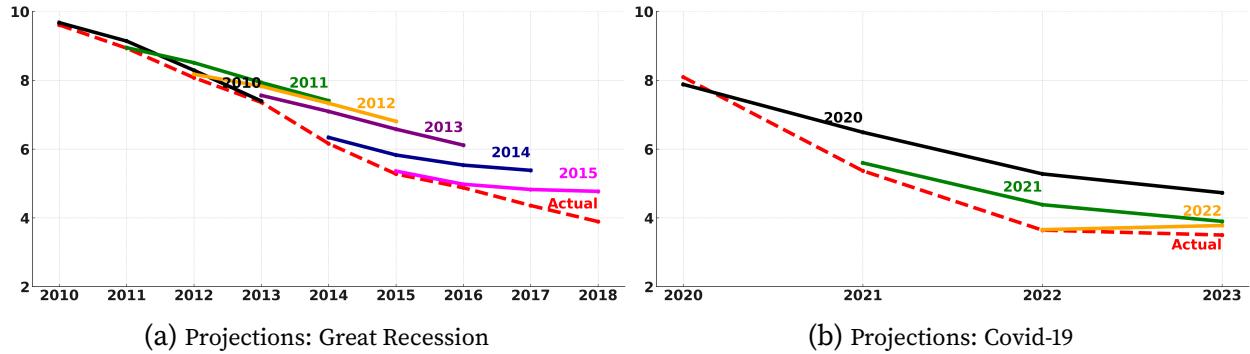


Note: This figure plots the recovery of unemployment rate and vacancies from recessions to their pre-recession levels. The vacancy series is from Barnichon (2010a)

A.3.1 Professional Forecasters.

Survey of Professional Forecasters. To illustrate this point, I first present unemployment projections from the Survey of Professional Forecasters (SPF) during the recovery from the Great Recession in Figure A2. This illustrates that a) the forecasters consistently predicted unemployment to be higher than it actually was during the recovery from the Great Recession and, b) this misperception about the true nature of the shock likely contributed to higher persistence, as the historical decomposition of unemployment rate in Figure ?? suggests. The SPF documents long run projections starting in 2009 and hence long run projections are not available for earlier recessions. However, I provide 1 year ahead forecasts in Figure A4a, which documents that forecasters almost always predict the recovery to be slower than it is.

Figure A2: Projected Unemployment Rate from Survey of Professional Forecasters:

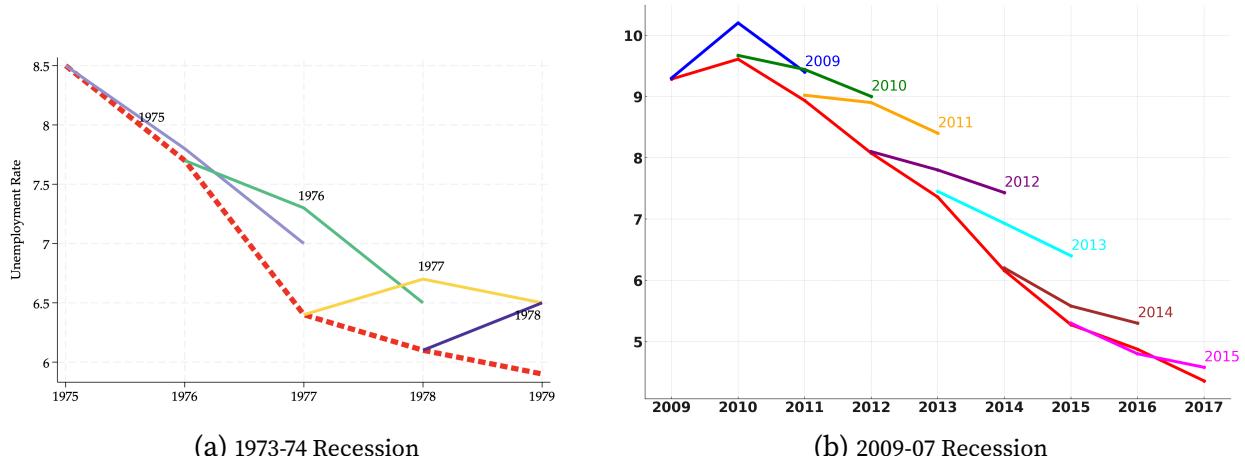


Note: The various colored lines represent the median 1 year, 2 year and 3 year ahead projection of unemployment rate from the Survey of Professional Forecasters. The solid red line is the actual unemployment rate

Livingston Survey The Livingston survey is the longest running survey of forecasters starting in 1946.¹⁹ The survey is conducted twice a year and consists of forecasts of 18 different variables describing unemployment, output, prices, and other macroeconomic data. The forecasts are by economists from industry, government, banking, and academia.

Figure A3 depicts the 1 year and 2 year ahead median forecasts by the forecasters in the Livingston survey for the 1973-74 recession in the left panel and the 2007-09 recession in the right panel. Qualitatively the results are similar to what the SPF forecasters expected. Across recessions, forecasters over estimated the recovery of unemployment rate. This re-enforces the idea that agents cannot distinguish between a persistent and transitory shock immediately and may take several quarters to learn.

Figure A3: Projected Unemployment Rate from the Livingston Survey

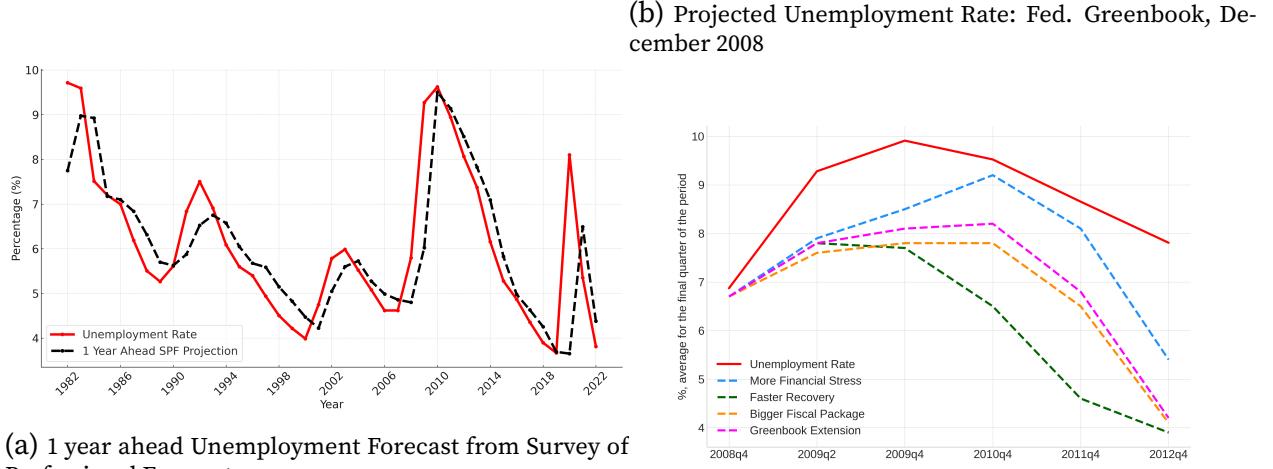


Note: The various colored lines represent the median 1 and 2 year ahead projection of unemployment rate from the Livingston Survey. The solid red line is the actual unemployment rate

¹⁹It is publicly available and is fielded by the Federal Reserve Bank of Philadelphia who took over from Joseph Livingston.

Policymakers. Now, to illustrate that it can be challenging even for policymakers to correctly assess the nature of the recession, I present the projections from Federal Reserve's Greenbook in December 2008 in Figure A4b. Under all scenarios, the Federal Reserve Board predicted a much faster recovery during the Great Recession.

Figure A4: Projected Unemployment Rate from the Livingston Survey



Note: Panel (a): The black dashed line represents the median 1 year ahead projection of unemployment rate from the Survey of Professional Forecasters. The solid red line is the actual unemployment rate. Panel (b): The black dashed line represents the projection of unemployment rate from the December 2008 Greenbook released by the Federal Reserve Board. The dashed lines represent projections under various scenarios that the Fed simulated. The solid red line is the actual unemployment rate.

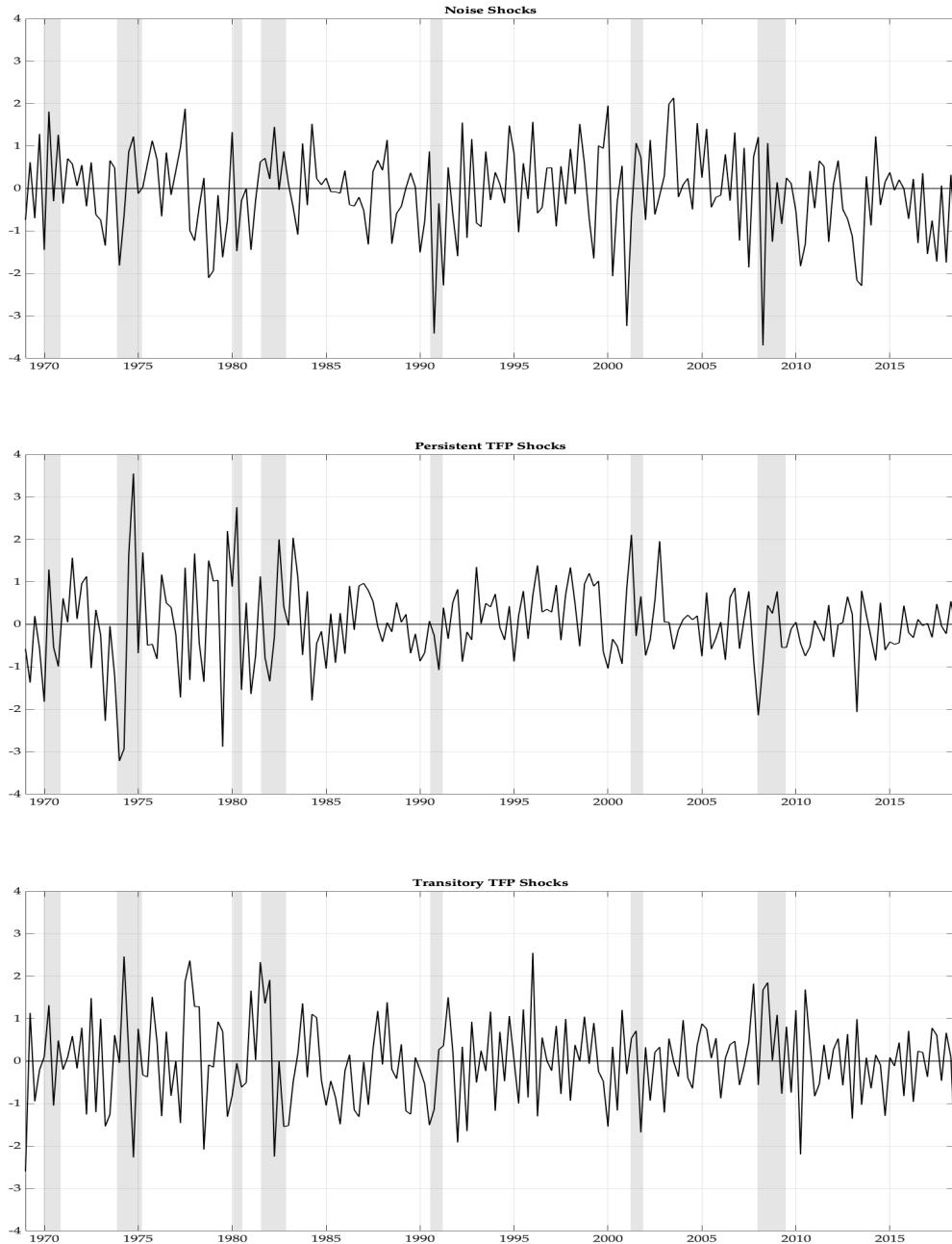
A.4 SVAR

In this section I discuss some more results and robustness from the SVAR. First, I present the shock series identified from the VAR in Figure A5.

VAR Impulse Response Functions. The VAR's impulse responses, illustrated in Figure A6, align with both the model's stipulated assumptions and economic reasoning. Specifically:

1. **Noise Shocks:** These do not affect TFP but instantly reduce nowcast errors while boosting GDP. These are imposed by the VAR on impact. However, we see in the dynamics that the nowcast errors remain negative for about 8 quarters which implies that the agents keep getting surprised as they expect GDP to be higher than it is. This suggests that they do not immediately recognize the shock as noise and attribute it to a persistent or transitory change in productivity. This is once again consistent with learning under imperfect information.
2. **Persistent Shocks:** These raise TFP in a manner that aligns with a long-lasting shock. Concurrently, GDP and nowcast errors increase immediately. Even after several quarters, nowcast errors stay elevated, indicating that these persistent shocks continually surprise economic agents and they misperceive the shocks.

Figure A5: Shock Series

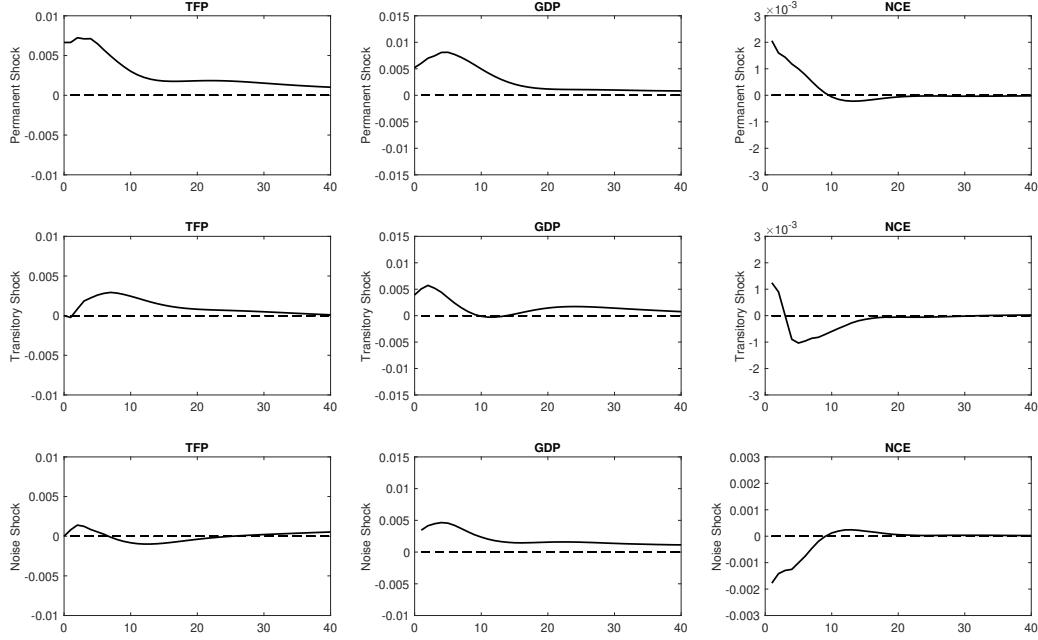


Note: This figure plots the time series of noise shocks, persistent TFP shocks, and transitory TFP shocks, as identified in the SVAR. The persistent TFP shocks have lower volatility post 1985 while the noise shocks have higher volatility.

3. **Transitory Shocks:** These momentarily elevate both TFP and output, but their effect is short-lived. Initially, nowcast errors rise due to these shocks but soon turn negative. This indicates that agents mistakenly view the shock as persistent for a duration and continue to be surprised since it's actually a transitory shock with minimal long-term effects on productivity and

GDP.

Figure A6: Impulse Response from the VAR



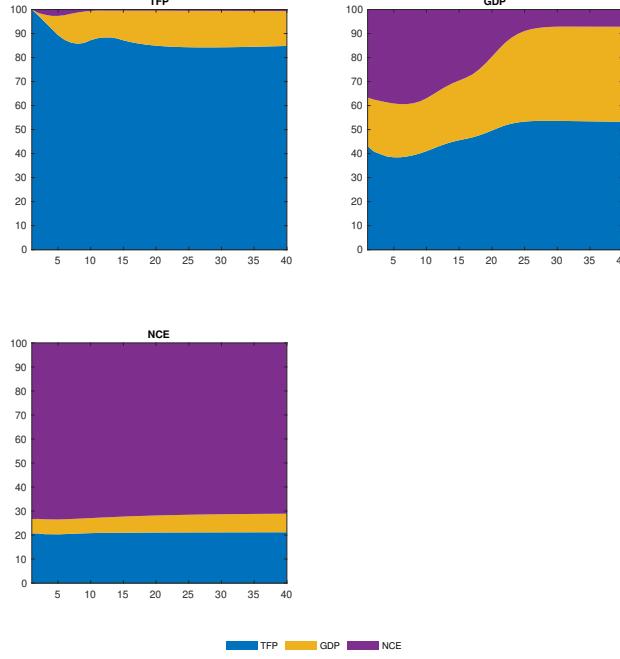
Note: This figure plots the impulse response functions for the variables in the VAR to a persistent shock, a transitory shock and a noise shock, identified using the SVAR described by the optimization problem in 6. The sample period is 1968q4: 2019q4.

The figure A7 plots the forecast error variance contribution of each shock to TFP, GDP and the nowcast errors (NCE). The blue shaded area is attributed to the persistent shock, the yellow is attributed to the transitory shock and the purple is attributed to the noise shocks. As expected, the maximum forecast error variance of TFP is explained by the persistent shock. We also see that the noise shock does not contribute significantly to the forecast error variance of TFP, which is consistent with the assumptions of the VAR. The nowcast errors are mostly explained by the noise shocks while GDP is initially explained to a large extent by the noise shocks but as the horizon increases, persistent shock becomes the primary driver of forecast error variance of GDP. This is also in line with economic intuition – as noise shocks die down, GDP is explained by the actual TFP shocks in the long run.

A.5 Smooth Linear Projections

In this section, I describe the method used to estimate the SLP, following Barnichon and Brownlees (2019). They model the sequence of impulse response coefficients as a linear combination of B-splines basis functions. These are estimated using a shrinkage estimator that shrinks the impulse

Figure A7: FEVD after Max-Share Identification



Note: This figure plots the forecast error variance decomposition for TFP, GDP and the Nowcast errors (NCE). The blue shaded area is attributed to the persistent shock, the yellow is attributed to the transitory shock and the purple is attributed to the noise shocks.

response toward a polynomial. SLP coincides with LP when the degree of shrinkage is low and with polynomial distributed lag model with a high degree of shrinkage. Consider a LP of the form:

$$(38) \quad y_{t+h} = \alpha_h^j + \beta_h^j u_t^j + \sum_{p=1}^P \gamma_p^j \omega_{t-p} + \mu_{h,t+h}^j$$

where ω_{t-p}^j is the set of lagged values of y and u^j .

Following Barnichon and Brownlees (2019), one can approximate $\beta_h^j \approx \sum_{k=1}^K b_k^j B_k^j(h)$ using a linear B-splines basis function expansion in the forecast horizon h . Thus, the corresponding smooth Linear Projections can be written as Equation 39.

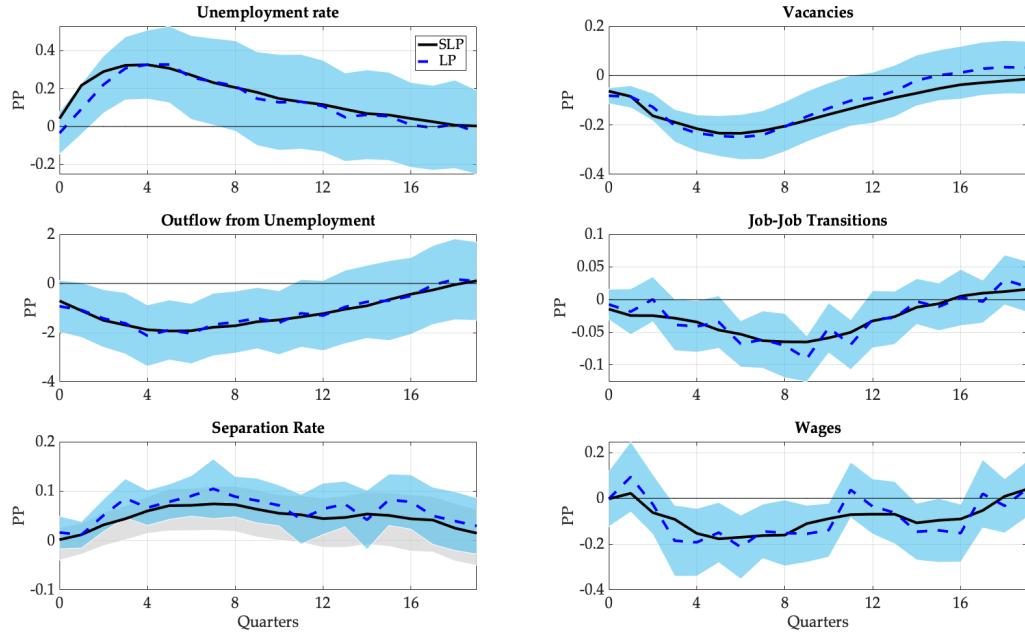
$$(39) \quad y_{t+h} \approx \sum_{k=1}^K a_k^j B_k(h)^j + \sum_{k=1}^K b_k^j B_k^j(h) u_t^j + \sum_{p=1}^P \sum_{k=1}^K c_{pk}^j B_k^j(h) \omega_{t-p}^j + \mu_{h,t+h}^j$$

The SLP is estimated using generalized ridge estimation. When the shrinkage parameter is small, it is close to the least square estimation and has zero bias but potentially large variance. When the shrinkage parameter is large, the estimator is biased but has smaller variance than the least squares estimator. The shrinkage parameter is chosen using k-fold cross-validation (Racine (1997)).

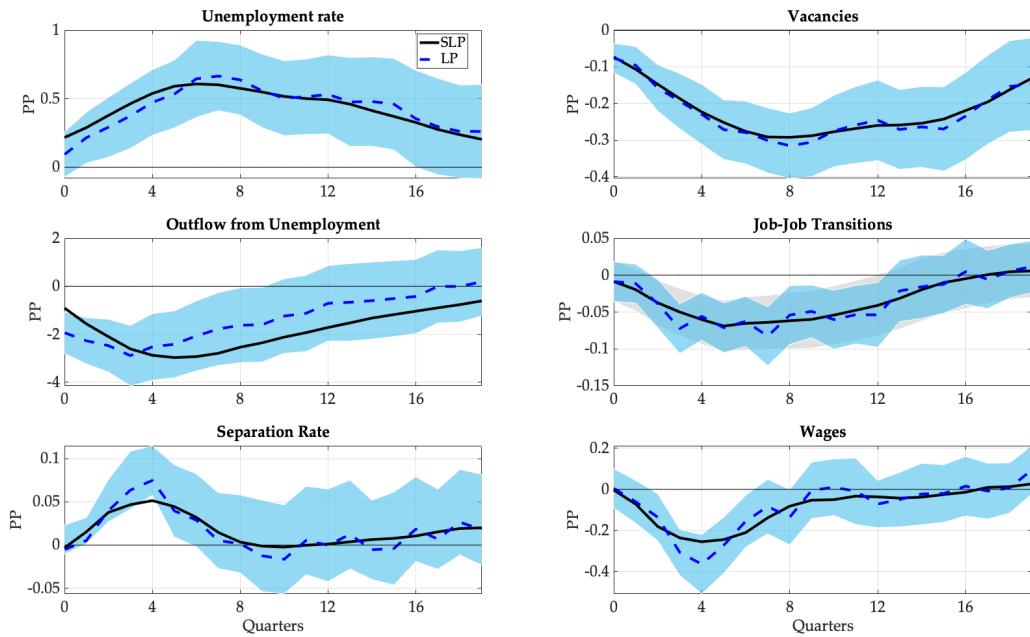
I present the impulse responses from the linear projection and their smoothed counterparts for the noise shock and the persistent shock in Figure A8

Figure A8: Impulse Responses from LP and SLP

(a) Noise Shock



(b) Persistent TFP Shock

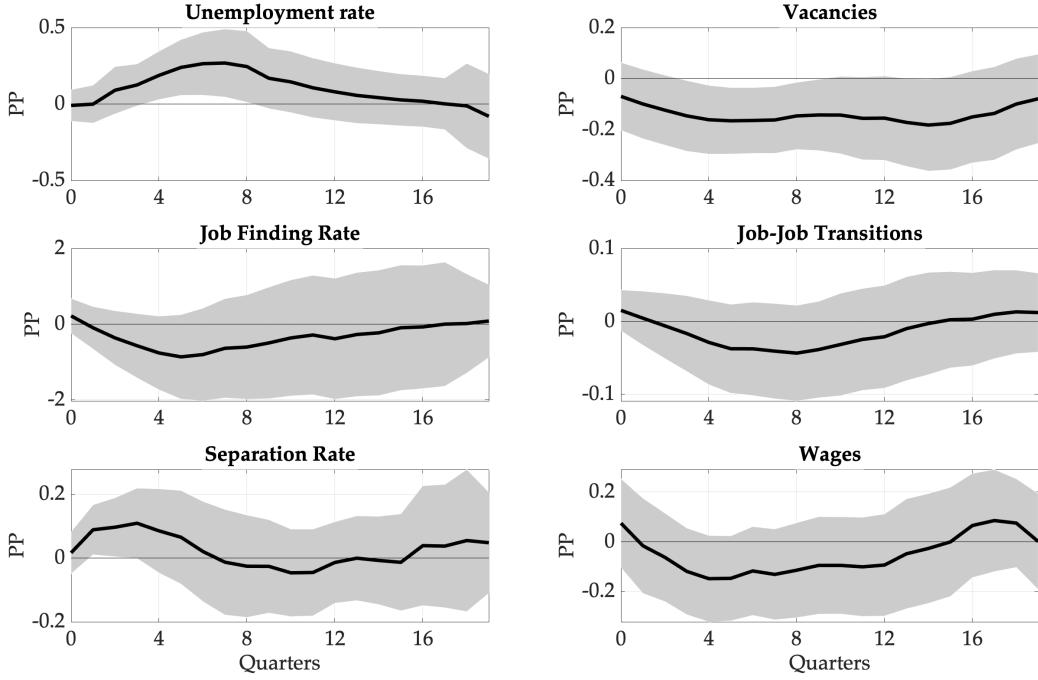


Note: This figure plots the impulse responses from the linear projection and their smoothed counterparts for the noise shock and the persistent shock.

A.6 Empirical Results

Impulse Response to Transitory TFP Shock Figure A9 illustrates the response of labor market variables to a transitory TFP shock. The response to a transitory shock is muted and is less than that of noise shocks in terms of magnitude.

Figure A9: Impulse Response to Transitory TFP Shocks



Note: This figure plots the impulse response functions for key labor market variables to a transitory TFP shock. The shaded area represents a 95% confidence interval.

Historical Decomposition To understand the role of imperfect information over the business cycle, it is useful to understand how much of the deviation of the key labor market outcomes from their predicted path can be explained by the productivity shocks. If noise shocks are not important, the productivity shocks would explain almost all the fluctuations in these variables. The VAR model in its Vector Moving Average form is

$$(40) \quad y_t = e_t + \Psi_1 u_{t-1} + \dots + \Psi_t u_1 + \bar{\Psi}_t$$

$$(41) \quad = \psi_0 v_t + \psi_1 v_{t-1} + \dots + \psi_t v_1 + \bar{\Psi}_t$$

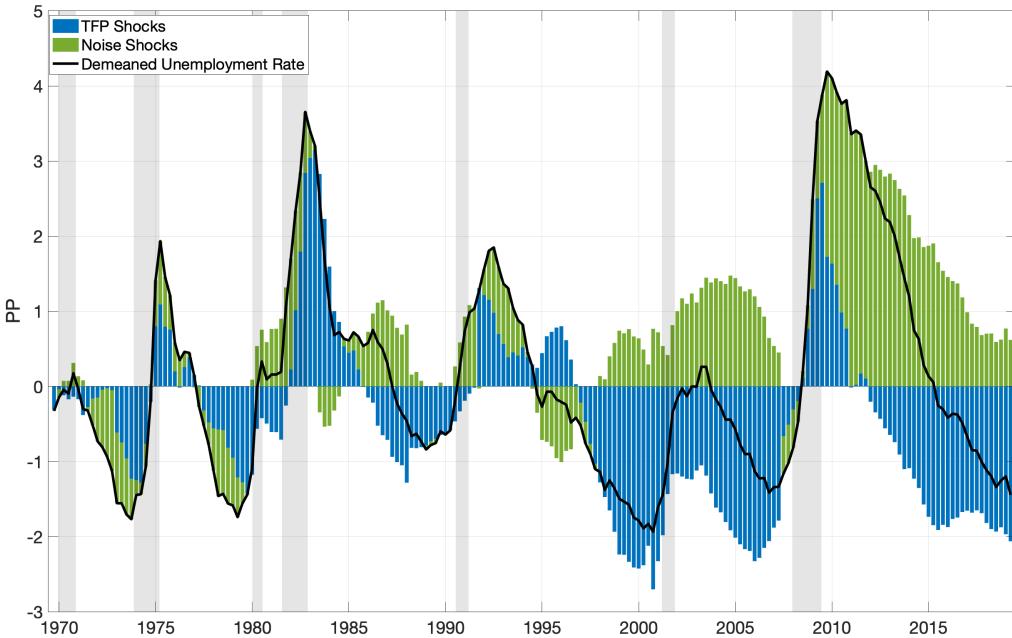
where, $\psi_0 = Q$ and $\psi_j = \Psi_j Q$ are functions of A_1, \dots, A_p and Q . $\bar{\Psi}_t$ is the pure deterministic

component. Now, we can decompose $(y_t - \bar{\Psi}_t)$ as the sum of the contribution of n shocks

$$(42) \quad y_t - \bar{\Psi}_t = \sum_{j=0}^t \psi_j \nu_{t-j}^1 + \dots + \sum_{j=0}^t \psi_j \nu_{t-j}^n$$

Here I present the unemployment rate predicted by combination of three shocks in the VAR.

Figure A10: Historical Contribution of Shocks to Unemployment Rate



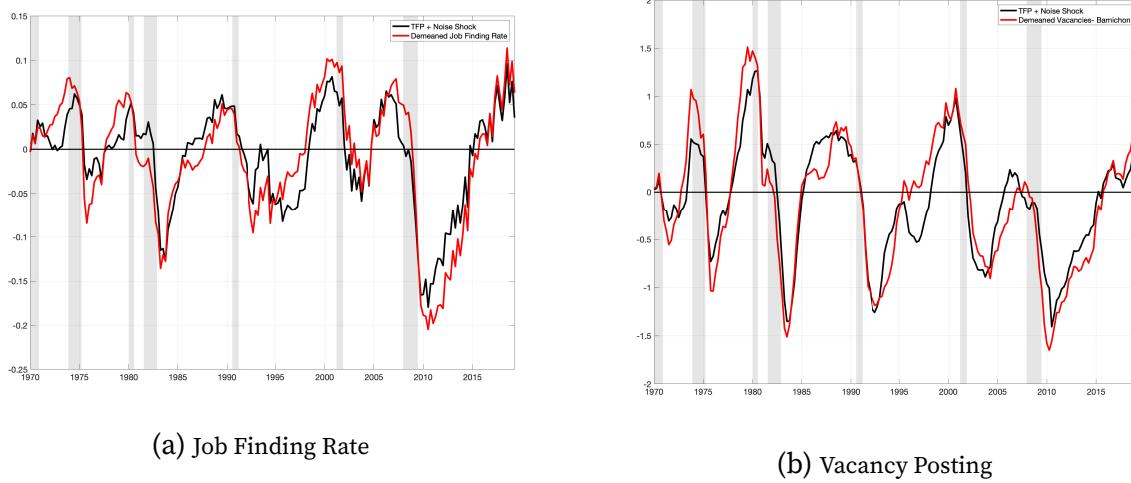
Note: This figure plots the historical decomposition of unemployment rate following equation 15. The blue bars are the cumulative contribution of the identified persistent and transitory TFP shocks to the movements in demeaned unemployment rate (red line). The green bars are the contribution of the noise shocks, which contribute significantly to the unemployment rate during the recessions in 1990-91, 2001 and 2007-09.

Persistence of Unemployment To understand the contribution of the noise shocks to the persistence of unemployment, I compute for each recession between 1968-2019, the share of the rise in unemployment during the recession that has been reversed during the expansion.

$$u_{recovery,t} = \frac{u_{peak} - u_t}{u_{peak} - u_{trough}}$$

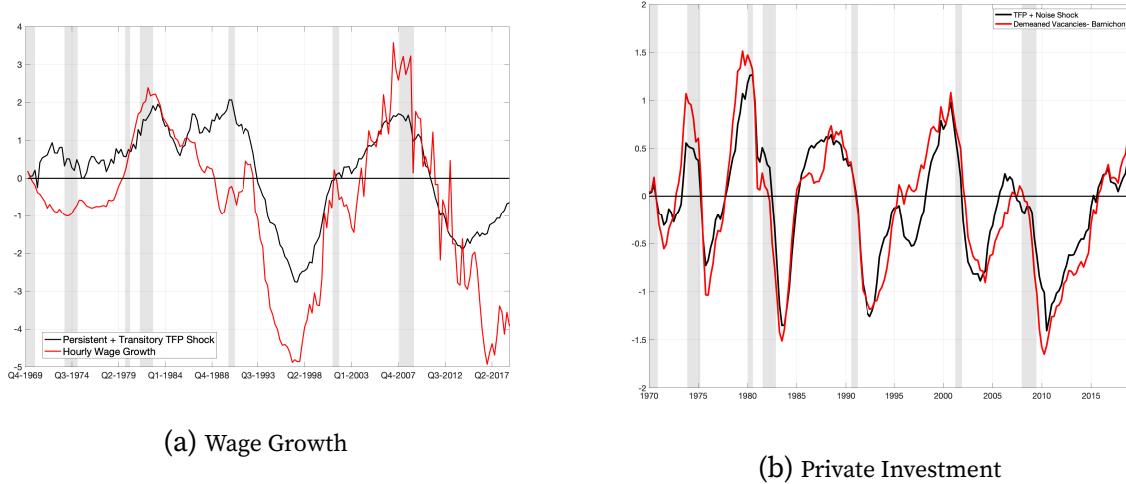
I then define persistence as the number of quarters to recover 50% of the rise in unemployment during a recession, that is $u_{recovery,t} = 0.5$. Now, from the historical decomposition, I can calculate what fraction of this persistence can be attributed to each of the shock by first computing the predicted unemployment rate from each shock and then calculating the persistence as defined

Figure A11: Historical Contribution of Persistent, Transitory and Noise Shocks



Note: This figure plots the historical decomposition for each series following equation 15. The black line is the cumulative contribution of the identified persistent, transitory and noise shocks to the movements in demeaned unemployment rate (red line).

Figure A12: Historical Contribution of Persistent, Transitory and Noise Shocks



Note: This figure plots the historical decomposition for each series following equation 15. For wage growth, the black line is the cumulative contribution of the identified persistent, transitory and noise shocks to the movements in demeaned unemployment rate (red line). For private investment, the blue bars are the cumulative contribution of the identified persistent and transitory TFP shocks to the movements in demeaned unemployment rate (red line). The green bars are the contribution of the noise shocks.

above. The results are summarized in Table A2. For the great recession, noise shocks account for about 35% of the 50% of the rise in unemployment and on average noise shocks account for 27% of this recovery across recessions.

Table A2: Contribution of Noise Shocks to Recovery of Unemployment Across Recessions

Recession	Data	No of quarters for 50% recovery
		Share explained by Noise shocks
2007-09	20	35%
2001	15	33%
1990-91	18	28%
1981-82	18	33%
1973-75	17	29%
Average	17.6	32%

Note: This table reports the number of quarters to recover 50% of the rise in unemployment during a recession, that is $u_{recovery,t} = 0.5$.

A.7 Robustness Exercises

The subsection conducts some more robustness exercises on the tri-variate VAR .

A.7.1 Sub-Sample Analysis

In this subsection, I discuss a sub-sample analysis to address investigate whether there were structural changes in the business cycle post the Great Moderation in 1985. I first present some simple statistics from the SVAR identified shocks as well as the nowcast errors in Table . I find that post 1990, the noise shock became more volatile while the persistent shocks have become less volatile. Interestingly, the unemployment nowcast errors not only became more volatile, but also the average flipped sign post 1990 implying that forecasters on an average, predict unemployment to be higher than it is in this period. Likewise for output growth, forecasters predict output to be lower than it is. This suggests some structural change that might have happened post Great Moderation, and I leave it for future work to investigate it's source.

A.7.2 Inclusion of COVID-19 recession

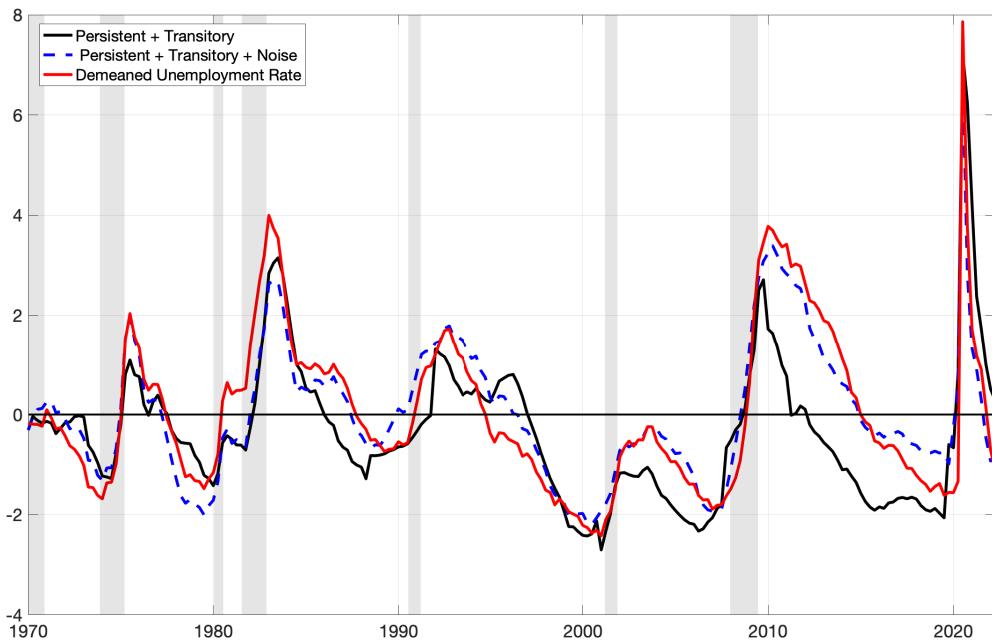
In this section, I extend the VAR by including the Covid 19 pandemic. However, it is important to note that to identify the shocks in the Covid years, I have to assume that the persistent shock maximizes the forecast error variance of TFP even in the short run. I plot the historical decomposition in Figure A13. The focus is however on noise shocks and it is evident that the noise shocks did not play an important role in this recession, as most of the fluctuation is picked up by the two TFP shocks. The reason might be because of the fact that forecasters predicted a much transitory recovery.

Table A3: Summary Statistics Pre and Post 1990

	1968-1989		1990-2019	
	Mean	SD	Mean	SD
Unemployment Rate	5.68	1.65	5.80	1.83
GDP Nowcast Error	0.06	1.72	0.25	2.59
Unemployment Nowcast Error	0.07	0.695	-0.03	1.20
Noise Shock	0.04	0.745	-0.05	1.27
Persistent Shock	-0.21	1.34	0.03	0.68
Transitory Shock	0.18	0.83	0.27	0.89

Note: This table reports summary statistics from 1968-1989 and 1989-2019 in the empirical exercise.

Figure A13: COVID-19: Historical Contribution of Shocks to Unemployment Rate



Note: This figure plots the historical decomposition of unemployment rate following equation 15. The black line is the cumulative contribution of the identified persistent and transitory TFP shocks to the movements in demeaned unemployment rate (red line). The dashed blue line is the contribution of the TFP shock and the noise shocks, which contribute significantly to the unemployment rate during the recessions in 1990-91, 2001 and 2007-09. The remaining movement here is explained by the 4th shock μ_t .

B Theoretical Appendix

B.1 Information Structure

Consider the following state-space representation:

$$\begin{aligned} z_t &= x_t + \eta_t, & \eta_t &\sim \text{iid } N(0, \sigma_\eta^2) \\ x_t &= \rho_x x_{t-1} + \epsilon_t, & \epsilon_t &\sim \text{iid } N(0, \sigma_\epsilon^2) \\ a_t &= x_t + n_t, \\ n_t &= \rho_n n_{t-1} + \nu_t, & \nu_t &\sim \text{iid } N(0, \sigma_\nu^2) \end{aligned}$$

Where:

- z_t is the observed sum.
- a_t is the observed public signal.
- x_t is the underlying state variable.

Kalman Gain Derivation The Kalman gain is derived from the following general equation:

$$(43) \quad K_t = P_{t|t-1} H' (H P_{t|t-1} H' + R)^{-1}$$

Given our system, the state transition matrix F :

$$(44) \quad F = \begin{bmatrix} \rho_x & 0 \\ 0 & \rho_n \end{bmatrix}$$

Observation matrix H :

$$(45) \quad H = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}$$

Process noise covariance matrix Q :

$$(46) \quad Q = \begin{bmatrix} \sigma_\epsilon^2 & 0 \\ 0 & \sigma_\nu^2 \end{bmatrix}$$

Measurement noise covariance matrix R :

$$(47) \quad R = \begin{bmatrix} \sigma_\eta^2 & 0 \\ 0 & 0 \end{bmatrix}$$

Using these matrices, the Kalman gain is:

$$(48) \quad K_t = P_{t|t-1} \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \left(\begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} P_{t|t-1} \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} + \begin{bmatrix} \sigma_\eta^2 & 0 \\ 0 & 0 \end{bmatrix} \right)^{-1}$$

In steady-state, the error covariance matrix does not change over time, i.e., $P_{t+1|t} = P_{t|t-1} = \bar{P}$. The steady-state Riccati equation is:

$$(49) \quad \bar{P} = F\bar{P}F^T + Q - F\bar{P}H^T(H\bar{P}H^T + R)^{-1}H\bar{P}F^T$$

From this equation, the variance of the estimation error for x_t in steady-state is given by \bar{P}_{11} . Given the structure of the processes, the Kalman gain matrix is given by

$$(50) \quad \mathbf{K}_t = \begin{bmatrix} \frac{1}{\sigma_z^2} & \frac{1}{\sigma_s^2} \\ \frac{1}{\sigma_z^2 + \frac{1}{\sigma_{x,t}^2} + \frac{1}{\sigma_s^2}} & \frac{1}{\sigma_z^2 + \frac{1}{\sigma_{x,t}^2} + \frac{1}{\sigma_s^2}} \end{bmatrix}$$

where, $\sigma_{x,t}^2$ is the conditional forecast variance of $x_{t+1} \equiv \text{Var}_t(x_{t+1})$. It is updated according to the standard Riccati equation:

$$(51) \quad \sigma_{x,t}^2 = \rho_x^2 \left(\frac{1}{\sigma_s^2} + \frac{1}{\sigma_z^2} + \frac{1}{\sigma_{x,t-1}^2} \right)^{-1} + \sigma_x^2$$

where,

$$(52) \quad \sigma_z^2 = \text{Var}(z_t) = \sigma_x^2 + \sigma_\eta^2$$

$$(53) \quad = \frac{\sigma_e^2}{1 - \rho_z^2} + \sigma_\eta^2$$

$$(54) \quad \sigma_s^2 = \text{Var}(\hat{s}_t) = \sigma_x^2 + \sigma_a^2$$

$$(55) \quad = \frac{\sigma_e^2}{1 - \rho_z^2} + \frac{\sigma_v^2}{1 - \rho_a^2}$$

B.2 Estimation: Full Information

In this section I present the results for re-calibration of the full information model to match the impulse responses from the persistent TFP shocks.

Table B1: Estimated Parameters from IRF Matching: Full Information Model

Parameters	Interpretation	Value	Target
Ψ	Match efficiency	0.48	Unemployment Rate = 0.055
κ	Cost of hiring	8.23	$U - E = 0.28$
μ	Scale parameter of search cost	0.082	$E - E = 0.025$
$1 - \sigma$	Separation rate	0.010	$E - U = 0.010$
ϕ	SS productivity from bad job	0.68	Δ Wage of E-E = 0.045
Parameters	Interpretation	Estimate	Std. Error
λ	Renegotiation frequency	0.88	0.13
ξ	Probability of finding a good job	0.18	0.05
η_h	Hiring cost convexity	0.34	0.09

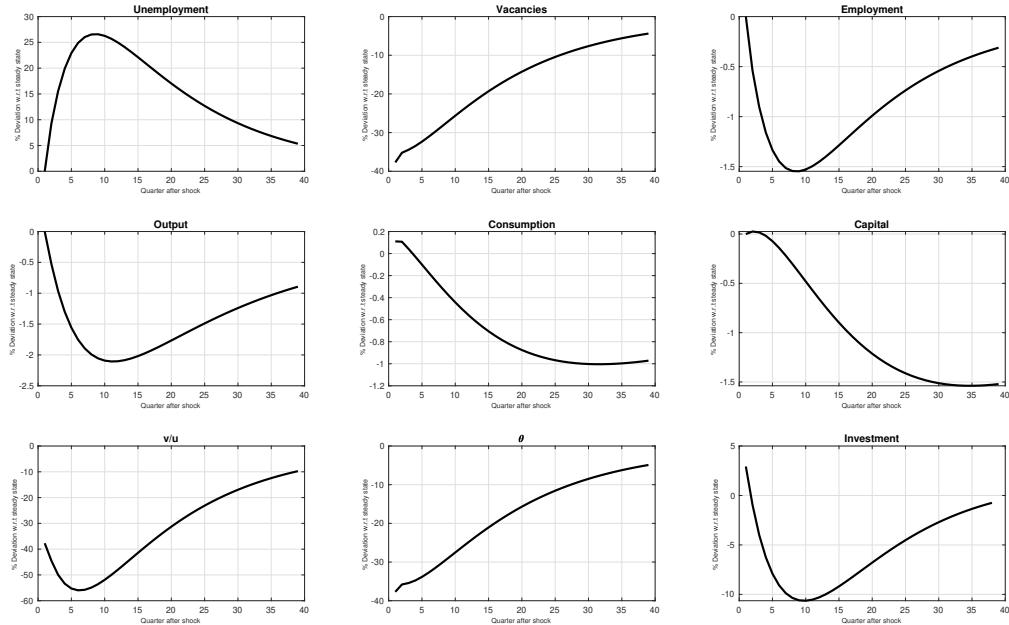
Note: This table reports the estimated parameters from the impulse response matching exercise outlined in equation 37 for the Full information model. The third column reports the estimated values while the fourth column reports the standard errors for these values. The impulse responses are matched by GMM and the standard errors are calculated using the delta method.

B.3 Quantitative Results

B.4 Impulse Responses From the Model

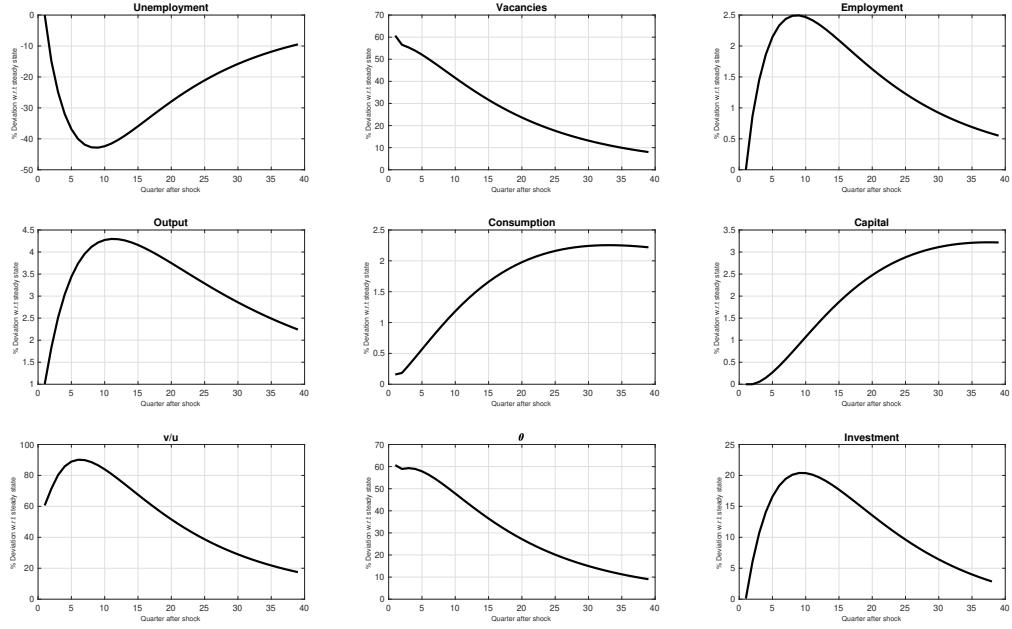
Here I plot impulse response functions from the imperfect information sticky wage with on-the-job search model for other important outcomes like output, investment.

Figure B1: Model Implied Impulse Response Functions to a Negative Noise shock



Note: This figure plots the model implied, impulse response functions to a noise shock.

Figure B2: Model Implied Impulse Response Functions to a Positive Persistent Productivity



Note: This figure plots the model implied, impulse response functions to a persistent productivity shock.

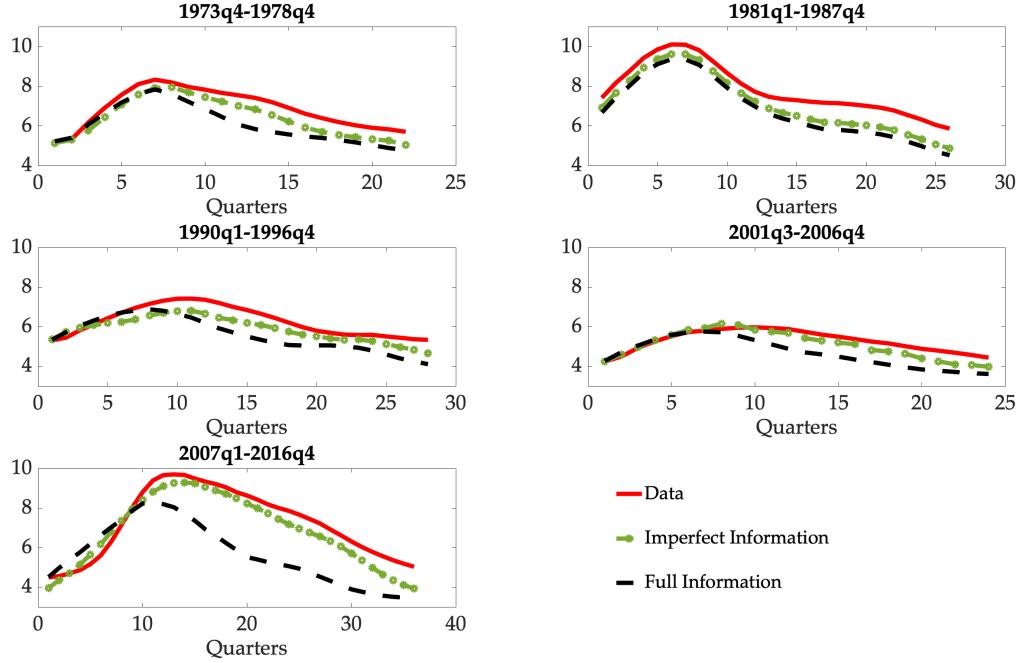
B.4.1 Unemployment Dynamics across Recessions: Data vs Model

The calibrated model is simulated to generate counterfactual unemployment rate series for 5 recessions between 1970-2019. This exercise shows that imperfect information explains the slow recovery of unemployment rate in the last three recessions. For this exercise, the model is normalized to match the starting unemployment rate for each of the recessions. While simulating the imperfect information model, each period, all three identified shocks from the VAR are incorporated. For the full information model, I only introduce the persistent and the transitory shocks each period. Furthermore, the full information model is re-estimated as described in the previous section, to match the empirical IRFs to the persistent TFP shocks. The estimated parameters for the full information model is presented in the Appendix.

B.4.2 Comparing Mechanisms in the Model

In this section, I compare the persistence and volatility of unemployment under various mechanisms with and without imperfect information. I compare the model under 4 scenarios: a) flexible wages without on-the-job search (OJS), b) flexible wages with OJS, c) sticky wages without OJS, and d) sticky wages with OJS.

Figure B3: Model Implied Recovery of Unemployment for Recessions



Note: This figure plots the model implied, simulated unemployment rate for the re-calibrated full information model (dashed blue line) and the imperfect information model (solid green line) for major recessions between 1973-2019.

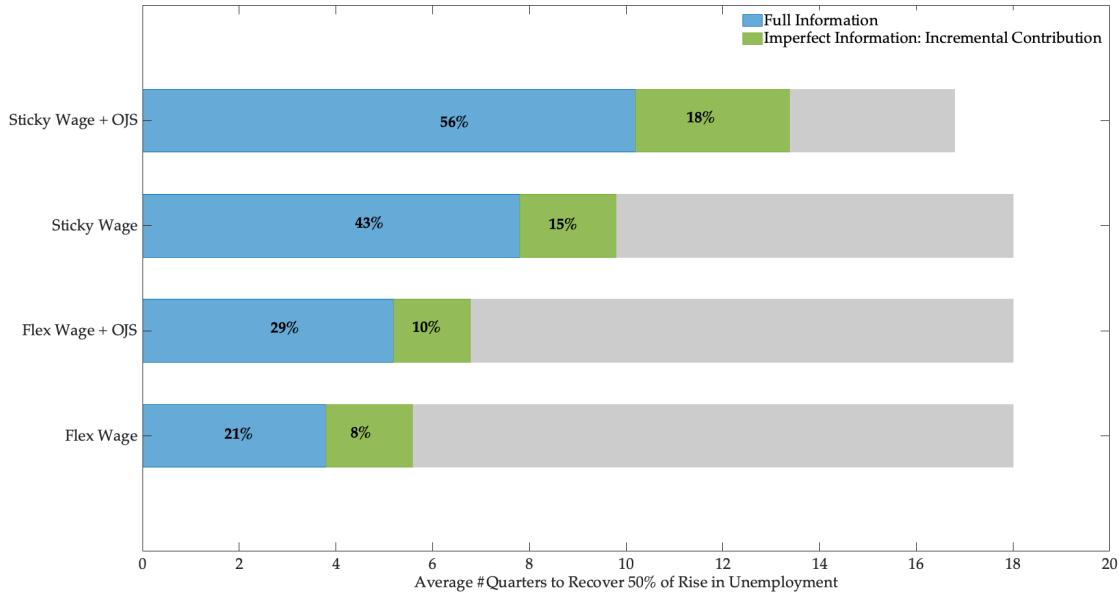
Persistence To capture the persistence of unemployment, I compare the average duration to recover the 50% of the rise in unemployment across recessions between 1968-2019. Figure B4 shows the decomposition for the four difference model specifications, and within each specification I further decompose the re-calibrated full information benchmark to the imperfect information model without noise.

The main takeaway of this graph is that introducing learning endogenously contributes to persistence in unemployment rate in the model. This speaks to Wright (1986), who finds that imperfect information (albeit about wages, and on worker side), introduces learning endogenously in presence of job search.

I also present the full duration of recovery across recessions in the Table B2 for the re-estimated full information model and the imperfect information model. This measure captures the duration of recovery by calculating the number of quarters it took the unemployment rate to return to its pre-recession trough.

Volatility In this section, I compare the unemployment volatility under various mechanisms with and without imperfect information. To highlight that learning contributes to volatility under each specification, I plot the unemployment volatility as a percent of the observed volatility in data in Figure B5. In the stacked bar graph, I compare full information benchmark to imperfect

Figure B4: Average Duration to Recover 50% of Rise in Unemployment Across Models



Note: This figure plots the model implied duration from the beginning of the recessions to recover 50% of the rise in unemployment. This is averaged across the recessions between 1968-2019, for various model specification. The percentages are the percent of the data (18 quarters) that the particular model specification explains, while the x-axis is the actual number of quarters explained by the particular specification. The green bars are incremental contributions by learning, which implies that the total contribution of the imperfect information model is the sum of the blue and the green bar. Here, the full information model is *not* re-calibrated and the noise is shut down in the imperfect information model. Further, I shut down each mechanism one by one in both models.

Table B2: Duration of Recovery of Unemployment Rate Across Recessions

Recession	Data	Full Information	Imperfect Information
1973-75	22	14	17
1981-82	24	17	21
1990-91	28	16	24
2001	24	14	21
2007-09	37	22	32

Note: This table reports the number of quarters it takes unemployment to return to pre-recession trough across five recessions between 1975-2019. The model is normalized to match the starting unemployment rate for each of the recessions. The imperfect information model is simulated each period with all three identified shocks from the VAR activated. For the full information model, only the persistent and the transitory shocks are incorporated each period. The full information model is then re-estimated to match the empirical impulse responses to the persistent TFP shocks.

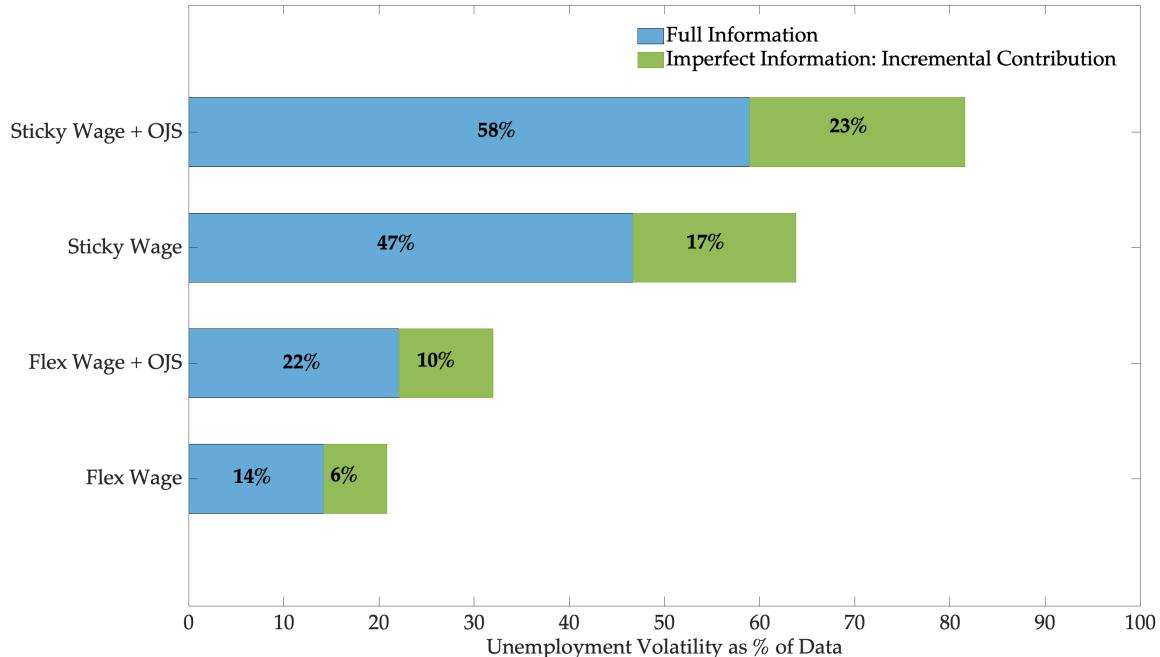
information model under 4 scenarios: a) flexible wages without on-the-job search (OJS), b) flexible wages with OJS, c) sticky wages without OJS, and d) sticky wages with OJS. I do not re-calibrate the full information model, but shut down noise in the imperfect information model.

Within the flexible wages without OJS framework, full Information framework accounts for approximately 14% of the unemployment volatility observed in the data. However, when introducing

imperfect information, volatility is markedly amplified, bringing the cumulative total to around 20%. In the flexible wage with OJS environment, while full information accounts for about 22% of the volatility, imperfect information's contributes an additional 10% to the unemployment volatility.

Introduction of sticky wages with no OJS contributes significantly to the volatility and under full information, it encompasses nearly 47%. This is not a surprising result as sticky wages have long been proposed as a mechanism to match the observed volatility of unemployment (Shimer, 2005). However, it is important to note that learning contributes an additional 17%. Finally, when OJS is introduced along with sticky wages, the full information model can predict about 58% of the volatility in the data, but importantly, the cumulative impact of imperfect information catapults it to a significant 81%. This underscores the substantial amplification by imperfect information across wage-setting contexts.

Figure B5: Unemployment Volatility as a % of Data Across Models



Note: This figure plots the model implied standard deviation for the unemployment rate across models. Here, the full information model is *not* re-calibrated, but noise is shut down in the calibrated imperfect information model. Further, I shut down each mechanism one by one in both models.

Table B3 compares the business cycle statistics obtained by simulating the imperfect information model as well the re-calibrated full information model, to the statistics in the US economy from 1968-2019 across multiple labor market variables such as output (Y), unemployment rate (U), job vacancies (V), job-to-job transitions ($E - E$), job transitions from unemployment to employment ($U - E$), and hiring rate. I compare full information benchmark to imperfect information model under 4 scenarios: a) flexible wages without on-the-job search (OJS), b) flexible wages with OJS, c)

sticky wages without OJS, and d) sticky wages with OJS.

The imperfect information model outperforms the full-information model across all specifications, highlighting that learning is an important mechanism for volatility in the labor market.

Table B3: Business Cycle Statistics

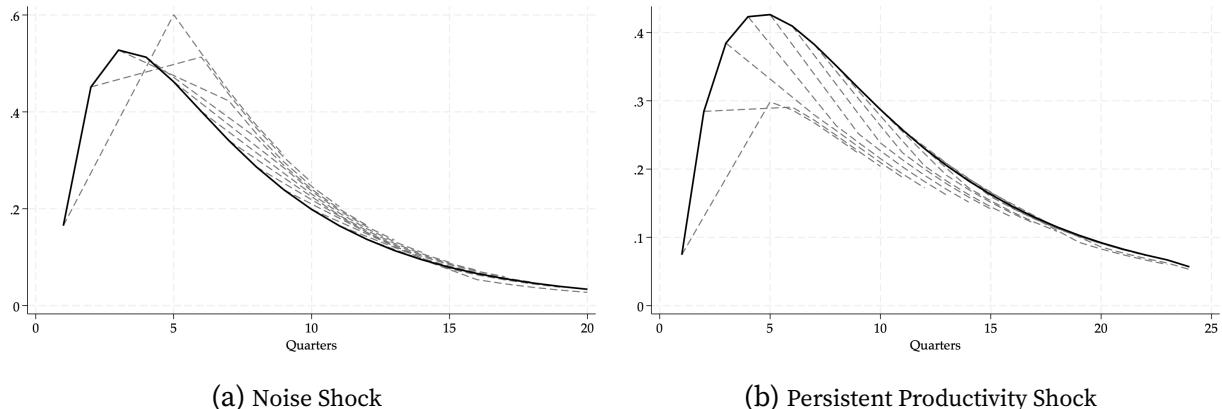
	Data (SD)	Flex Wage , No OJS		Flex Wage , OJS		Sticky Wage , No OJS		Sticky Wage , OJS	
		Full Info	Imperfect Info	Full Info	Imperfect Info	Full Info	Imperfect Info	Full Info	Imperfect Info
Y	0.019	0.009	0.014	0.011	0.017	0.013	0.021	0.018	0.027
U	0.162	0.029	0.068	0.052	0.098	0.087	0.128	0.102	0.153
V	0.182	0.032	0.091	0.072	0.136	0.101	0.176	0.131	0.193
U-E	0.069	0.019	0.031	0.027	0.042	0.032	0.061	0.048	0.077
E-E	0.102	0.017	0.039	0.042	0.063	0.036	0.055	0.069	0.086

Note: This table reports standard deviation of key labor market variables in the model. The data here has been simulated from the model and HP-filtered (100,00).

B.5 Projections from the Model

In this section, I present the 4-8 quarters ahead projections by the agents in the model in response to a persistent TFP shock and in response to a noise shock. When faced with a persistent TFP shock, due to imperfect information, agents attribute a part of the shock to be noise as well as transitory shock and hence their projections under-react to the actual unemployment rate. However, the reverse happens when they face a noise shock. They similarly attribute some part of the shock to be persistent or transitory productivity and hence initially expect unemployment to be higher than it actually is (since true productivity has not changed). They eventually start placing more and more weight on the shock being noise and as they learn, their projections are truer to the actual.

Figure B6: 4-8 Quarter Ahead Projections in the Model



Note: This figure plots the r4-8 quarters ahead projections by the agents in the model in response to a noise shock (a) and a persistent TFP shock (b). The solid thick black line is the actual response of unemployment due to these shocks respectively.