Nonlinearities in Monetary Policy Transmission

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Abstract

First order approximations of a model's impulse response functions cannot capture non-linear behavior in shock transmission. Namely, it's possible that big shocks are not a scaled version of small shocks (size effect) or that responses following a positive shock do not mirror those from a negative shock (asymmetry). Using a Local Projection Instrumental Variable (LP-IV) framework, I estimate impulse responses of standard macro variables to monetary policy shocks and look for evidence of nonlinearities. Specifically, I use monetary policy surprise series as an instrument and decompose the measured shock into regimes based on how the Fed Funds Rate changed in a given month to allow for nonlinearity. I find evidence against the notion that larger shocks amplify the effects of smaller shocks and some instances of broader asymmetry. Future work will gauge how well this result holds up with other estimation approaches (e.g., VAR-based, non-parametric, Bayesian methods) and investigate if enriching standard model frictions helps produce impulse responses that align with US data.

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Introduction

Much of the evidence on the effects of monetary policy has been produced from model-based and empirical approaches that impose a linear relationship between shocks and real variables. Namely, while standard impulse response functions (IRFs) can be a non-linear function of time, it's often the case that if the impulse response to a shock s_t is $\{y_{t+h}\}$, the impulse response to αs_t is simply $\{\alpha y_{t+h}\}$. This rules out non-linearity from a shock's *size* (big and small don't have the same effect) and *sign* (positive and negative don't have symmetric effects). To produce any meaningful policy recommendations, it must be determined whether this simplification is consequential.

The first stage of this project will consist of estimating IRFs from US data of standard macro variables to monetary shocks in a way that allows for non-linearity. This will be accomplished by using monetary surprise measures that are well-established in the literature (e.g., Romer and Romer, 2004; Nakamura and Steinsson, 2018), in combination with specifying regimes that correspond to the relative size and sign of change in the Federal Reserve's target federal funds rate in a given month. Then, we will see how well "off-the-shelf" models are able to match the nonlinearities we do observe. By construction, typical formulation and solution methods for standard models produce near or exactly linear IRFs. To make this model comparison exercise consequential, we modify the default constraints faced by firms (e.g., price and wage setting rigidities) and households (e.g., investment adjustment costs) to accommodate potential asymmetries, which also shed light on the extent to which the status quo structure dictates the results these models produce. Finally, we will consider further departures from the representative agent and full information paradigm to account for and ultimately rationalize what we observe.

The results gathered so far imply a substantial degree of non-linearity. For both negative and positive shocks, we find evidence of size effects for consumption, output (industrial production), and inflation (CPI growth). Specifically, we find evidence that modest, expansionary changes to monetary policy increase our macro variables of interest relatively more than a large change. Relativity in this context means that the effects of a small interest rate cut (a movement smaller than 10% of the Fed's previous target) are proportionally larger than a big cut. We also find that larger, counteractions changes have relatively less effect on inflation, while simultaneously producing a stronger depression in the level of consumption and output. To put these results in perspective, Table 1 gives a comparison in levels for a horizon of 12 months. For sign effects, we find evidence that there are asymmetries between a big cut and a big hike but the evidence for small changes is inconclusive.

Table 1: Difference in YoY growth between large shock and scaled small shock

	Cut Size Effect	**Hike Size Effect**
Consumption	-3.5%	-2.2%
Output	-8.4%	-3.8%
Inflation	-2%	0.9%

All estimates significant at 90% level

The bedrock of the parametric approach will be a Local Projection Instrumental Variables (LP-IV) framework advanced by Jordà et al. (2015) and fleshed out by Stock and Watson (2018), which offers several advantages over alternatives. For deciding between a LP or a vector autoregressive estimation (VAR), Plagborg-Møller and Wolf (2021) clarifies that in finite samples, this decision comes down to a trade-off between flexibility (LP) and efficiency (VAR). Notable advantages for LP are the insensitivity to the presence of unit roots or non-stationary variables as both outcome and control (Plagborg-Møller and Montiel Olea, 2021; Plagborg-Møller et al., 2024) and the ability to relax the assumptions imposed by VAR structure (namely, invertibility and recursiveness). For deciding between LP and LP-IV, the various monetary shock series that have been developed still have unresolved interpretability issues (e.g., Brennan et al., 2024), but what is consistent across all approaches is that they are developed in order to capture relevant changes in monetary policy while maintaining exogenous variation. Thus, it's more appropriate to treat these shock series as instruments. Moreover, by instrumenting actual changes to the interest rate target, we can argue the coefficients produced in our estimation are representative of the effects of monetary policy in general, rather than just policy surprises. Finally, we could in principle use a different shock series for each regime of our decomposition, so we can simply use whichever one is the strongest instrument for a given regime. Doing so with a pure LP estimation would yield incomparable parameters.

The main disadvantage of LP-IV relative to LP is the inability to incorporate state dependence. It should be noted that the virtually all past approaches claiming to estimate impulse responses from state-dependent local projection estimation (as well as many VAR-based approaches) likely suffer from substantial bias for non-marginal shock sizes (Gonçalves et al., 2024). Jordà (2023) proposes a fix using a very specific type of interaction term framework, but it cannot be extended to LP-IV without suffering from the curse of dimensionality. In any event, Gonçalves et al. (2024) provide a simple non-parametric procedure to properly estimate state-dependent effects, which we can augment with instruments and additivity to account for sample size[1] and shock interpretability issues. Because the sensitivity to state dependence should be taken seriously (e.g., large cuts tend to happen when the expected trajectory of output is downward sloping regardless of policy), this is an important benchmark. Another previously referenced disadvantage of LP is the relative size of standard errors. We can consider Bayesian extensions to our approach in the spirit of Ferreira et al. (2024). Moreover, I plan to try all described estimation procedures to provide a frame of referenced. So far, the LP and state-dependent LP results have yielded qualitatively the same results for nearly all variables and various shock series[2].

[1]Sample size is a constraining issue in general, given the need to include lagged outcome and control variables for all specifications. This, in addition to the desire to include the entire zero lower bound episode and subsequent tightening, prevents the use of series with arguably superior identification strategies such as Aruoba and Drechsel (2023), Acosta (2023) and Miranda-Agrippino and Ricco (2021)

[2]Bauer and Swanson (2023) and Bu et al. (2021), in addition to those previously mentioned. The shock series mentioned in footnote 1 are also considered in the litany of ancillary estimation results, namely LP without IV.

Related Literature: This work connects to a vast empirical literature attempting to assess the effects of monetary policy using data rather than specifying a general equilibrium model. Most papers use a version of a LP or VAR specification and deal with reverse causality issues with "monetary surprise" data from a previous effort (e.g., Romer and Romer, 2004) to identify unanticipated changes in monetary policy. Ramey (2016) provides a survey of the most common approaches, with Plagborg-Møller and Wolf (2021) clarifying the finite sample setting accounts for most of the differences. Moreover, Ramey (2016) documents prevalent "puzzles", implications of impulse responses that conflict with standard intuition, that exist for different pairings of method and monetary surprise measure. The guidance suggests the bias in VARs can be prohibitive in our application. In general, there is a great degree of ambiguity about what conclusions to draw about the empirical impulse responses to monetary shocks – one can find a well-cited paper suggesting that fundamental macro variable x responds in y direction for any combination of x and y. Another benefit to the framework I'm using is my main purpose largely abstracts from the notion of puzzles by focusing on *relative* effects, which carries a general lack of strong prior beliefs because it has not been extensively documented in past theoretical or applied analysis of monetary policy transmission.

Broadly speaking, the group of popular methods has remained the same over the past decade. But because of recently revealed shortcomings much of the literature relating to bias in estimates (Gonçalves et al., 2024; Herbst and Johannsen, 2024), bias in standard errors (Plagborg-Møller and Montiel Olea, 2021; Herbst and Johannsen, 2024), and general identification (Stock and Watson, 2018; Jordà, 2023), there is a need to provide new results that account for these considerations, which will also give insight into the usability of what already exists. This work will also be one of a very small group to explicitly focus on nonlinearities. Barnichona and Matthes (2018) estimate impulse responses through a vector moving average representation with some structural restrictions and present overwhelming evidence of sign asymmetries. Consistent across 3 identification strategies, they find that the effects of rate hikes and cuts move unemployment and inflation in the *same* direction, with the specification restricting nonlinearities yielding much different conclusions. Despite the moderate body of evidence pointing to LPs as being more appropriate for recovering reliable point estimates of monetary policy effects, Lee (2023) is the only preexisting work to try to allow for any non-linearity in a LP to my knowledge. Of course, the issue of LP vs. VAR remains an unsettled question – Stock and Watson (2018), for instance, conclude that inevitability is a relatively innocuous assumption for this application. However, the monetary shocks identified by Debortoli et al. (2023), which to my knowledge is the most general VAR-based approach in the literature (e.g., relaxes ordering assumption, permits general nonlinear functions of variables as controls), are highly counterfactual, anecdotally suggesting at least one of the standard assumptions is highly non-trivial to impose.

The route I am taking is not without its own potential pitfalls. As previously referenced, LP-IV cannot feasibly incorporate state dependence. A separate issue that interacts with the LP-IV specification is the validity of the instruments themselves. Jarocinski and Karadi (2020) and Acosta (2023) present evidence that when using monetary policy surprise measures, it may be important to not assume that Fed announcements (and monetary surprise measures in general) only affect people's beliefs about interest rates, i.e., they argue it's important to account for a "Fed information effect". Koo et al. (2024) are the first to document formally how this affects inference when using impulse responses generated by LP-IV. The monetary policy surprise literature has yet to reach a consensus on several key issues (Acosta, 2023; Brennan et al., 2024), crucially including how justifiable different identification strategies are across the array of shock series you can choose from, which adds another reason to consider a non-parametric approach. At the same time, this also creates merit for the parametric approaches by getting a better sense of how monetary surprise measures differ in various settings.

After a careful empirical treatment, the next step is to take our fact finding to models themselves, so this research also adds to the literature on model-based accommodations of nonlinearities. One well-documented cause of model nonlinearities is the effective lower bound (ELB). In particular, the standard New Keynesian model has several counterintuitive implications about optimal policy when the economy is sitting at the bound (e.g., Eggertsson, 2011; Christiano et al., 2011; Wieland, 2019). However, Bonciani and Oh (2023) find that many of these "paradoxes" are resolved by allowing the central bank to conduct a wider array of open market operations, as was common during the ELB episode of the 2010s. There has been in general a lot of attention paid to the idea that tight and loose monetary policy do not have mirroring effects (e.g., Coibion, 2012; Angrist et al., 2016; Tenreyro and Thwaites, 2016). For instance, some posit that monetary policy is less effective during business cycle downturns because it's easier to suppress rather than stimulate economic activity (e.g., encouraging vs. discouraging borrowing), a phenomena known as "pushing on a string". One associated source of asymmetry could relate to the evidence, dating as far back as Keynes (1936) and Tobin (1972), that there are relatively more frictions of revising prices and wages downward. Kim and Ruge-Murcia (2009) is the canonical reference for introducing more costly downward price and wage adjustment asymmetry into a New Keynesian model, but they assume a non-stochastic monetary policy rule. Lee (2023), the closest companion paper, uses an asymmetric investment constraint and simpler downward wage adjustment asymmetry and finds both sign and size asymmetries. Future work will extend beyond menu cost models, especially in light of Oh (2020) finding that under uncertainty shocks (unexpected increases in the second moments of exogenous processes), in particular that Calvo pricing yields more non-linear behavior resulting from these shocks compared to Rotemberg.

Empirical Methodology and Results

Parametric (LP-IV)

The impulse responses generated by local projections (LP), pioneered by Jordà (2005), are a collection of coeficients $\{\hat{\alpha}_h\}$, where each $\hat{\alpha}_h$ comes from a regression of y_{t+h} on time t control variables X_t and shocks s_t

$$y_{t+h} = \alpha_h s_t + \beta_h X_t + \epsilon_{t,h}$$

Because each of these regressions are independent of one another, this is a non-linear impulse response function (IRF). However, this is only non-linear with respect to the time horizon, not the shock itself. For our purposes, we are interested in how these IRFs vary when the shocks take different forms. Specifically, if big shocks and small shocks are just scaled versions of one another, or if positive and negative shocks (of the same size) produce mirror image effects. By construction, the default setup imposes that nonlinearities of this kind cannot exist. To modify the usual LP framework to accommodate these considerations, we can decompose our shock into several shock series based on what "regime" of monetary policy we are in. We consider that regimes vary along two dimensions: size (big or small) and sign (positive and negative), resulting in 4 regimes total

1.BH (Big Hike)   2.BC (Big Cut)   3.SH (Small Hike   4.SC (Small Cut)

In an econometric model, this regime setup amounts to an indicator variable that activates when the monetary policy change that occurred coincides with a given regime. Formally, the vanilla LP decomposition becomes

$$y_{t+h} = \underbrace{\alpha_h^R R_t s_t}_{(\alpha_h^{BH} r_{1,t} \,+\, \dots \,+\, \alpha_h^{SC} r_{R,t})\, s_t} + \beta_h X_t + \epsilon_{t,h}$$

where α_h^R is a 1×4 matrix of coefficients and R_t is 4×1 matrix of the corresponding regime indicator variables, which can be generalized to more regimes as needed. One interpretation of this setup is that there are 4 shocks[3], one of which will be "activated" in each period.

This setup requires one to set a definition for what constitutes a large change in monetary policy. We use a cutoff of a 10% jump from the previous fed funds target, which balances the sample sizes between all 4 regimes nicely. The ultimate tradeoff is that no changes close to the zero lower bound are classified as small if we use percent change, whereas no changes far enough away are classified as big if we use 50 basis points. Percent change is used because it captures the spirit of relative movement that motivates our framework. However, more attention is needed to consider the effective lower bound (ELB) episode. Some (e.g., Acosta, 2023) have used the Wu and Xia (2016) shadow rate, which is meant to capture how interest rates "would have moved" if the ELB didn't bind.

[3] In a pure LP setup, there would also be a fifth regime for when there is no change in the LP target. However, because we are using LP-IV and thus instrumenting changes in the target, there is no such regime in LP-IV and thus this is omitted from the initial setup for clarity

However, the month to month changes are too volatile for this to be a reasonable interpretation ex post. Another option could be tracking high frequency movements in shorter-term bond yields around Federal Reserve press.

Variable selection in general needs to be handling with care. Any attempts to collect empirical evidence about the effects of monetary policy must grapple with the identification issues from simultaneity (our outcome variables of interest influence the probability of "treatment") and general anticipation (our model will be misspecified if people are responding to something different than the series of observed policy changes). There have been a litany attempts to construct monetary surprise measures that reflect unanticipated change relative to what people expect. Using a high-frequency window around monetary policy announcements to construct these series is a common way to argue for plausible exogeneity, or that their data is soley capturing responses to central bank action. Because these measures can be normalized in different ways (Acosta, 2023) or have interpretation that is sensitive to units or specification (Brennan et al., 2024), it seems less appropriate to include them in estimation procedures directly as regressesors. Rather, we can leverage the fact that they are constructed to satisfy the usual IV assumptions of relevance and exogeneity (a sufficient condition for the exclusion restriction).

Thus, we proceed with the LP-IV approach put forward by Jordà et al. (2015) and crystalized by Stock and Watson (2018). I find that the Romer and Romer (2004) monetary surprise series is a strong instrument for all regimes except "small cut", for which I instead use Bauer and Swanson (2023). For implementation, we use GMM, where the moment conditions are the exclusion restrictions. This is equivolent to 2SLS in the case where the number of endogenous variables is equal to the number of instruments, and while this is not the case in our setting, I find that 2SLS yields nearly identical point estimates. As previously mentioned, LP faces efficiency concerns [4]. A common way standard errors have been estimated is using a Newey-West adjustment, which theoretically accounts for heteroskedasticity and autocorrelation (HAC), but Herbst and Johannsen (2024) finds this procedure yields biased estimates and should not be used for LP impulse responses. Rather than introducing unneeded complexity by using a more sophisticated HAC-robust method, Plagborg-Møller and Montiel Olea (2021) shows that using the usual Huber-White heteroskedasticity-robust standard errors paired with including a sufficient number of lagged control variables is sufficient. Plagborg-Møller and Montiel Olea (2021) also show LP is remarkably robust to the presence of unit roots and non-stationary variables. In my setting, I find supporting evidence for their result; estimating in differences and summing for the cumulative effect in levels produces very similar IRFs to estimating in levels directly, despite that some of the outcome variables are highly non-stationary (McCracken and Ng, 2016).

Following Ramey (2016), we consider outcome variables at a monthly frequency of inflation (CPI), output (industrial production), 1 year treasury yields, excess bond premium (Favara et al., 2016), and add real consumption expenditures. We focus on inflation, output, and consumption because of the ability to take the findings directly to

[4]An advantage of LP-IV is since we're able to use a different shock series for each regime, we can simply select the strongest instruments for efficiency gains. This is a similar dynamic to components of VAR models that are only estimated over subsamples (Gertler and Karadi, 2015)

standard models. Estimating in logs, a baseline approach of estimating in differences has an approximate percent change interpretation: $\widehat{\alpha}_h$ is represents the percent change in y_{t+h} relative to y_t given a shock occurred at t (all else equal). At $h = 12$, this takes a nice form of the change in year over year growth. For other horizons, we have the option of "annualizing" the growth rates, but this produces some unduly large values at short horizons because of the "all else equal" component (i.e., the other controls have a lot more offsetting weight that we aren't observing). To streamline interpretation without adding distortions, we can plot in terms of standard errors.

For capturing potential nonlinearities related to size ("size effects"), we are interested in whether the coefficient for a big change is meaningfully different from a small change. If we normalize this difference by the standard deviation of the small change coefficient, the interpretation of the resulting object is "standard deviations away". For example, if $\frac{\hat{\alpha}^{BC}-\hat{\alpha}^{SC}}{\sigma^{SC}} = 3$, the interpretation is that the big cut coefficient amounts to a 3 standard deviations away realization of the small cut coefficient. We can get confidence bands on this object through the variance-covariance matrix. If we instead normalized by the standard deviation of the *difference*, we'd simply have a t-statistic. As a guideline for interpretation, we can infer there is a size effect if the estimate is bounded away from 0, infer there is no size effect if we have a precise estimate near 0, and cannot say anything if we have point estimates far from 0 but wide confidence intervals. Figure 1 shows that significant size size effects exist for all variables and both positive and negative monetary policy changes at some horizon.

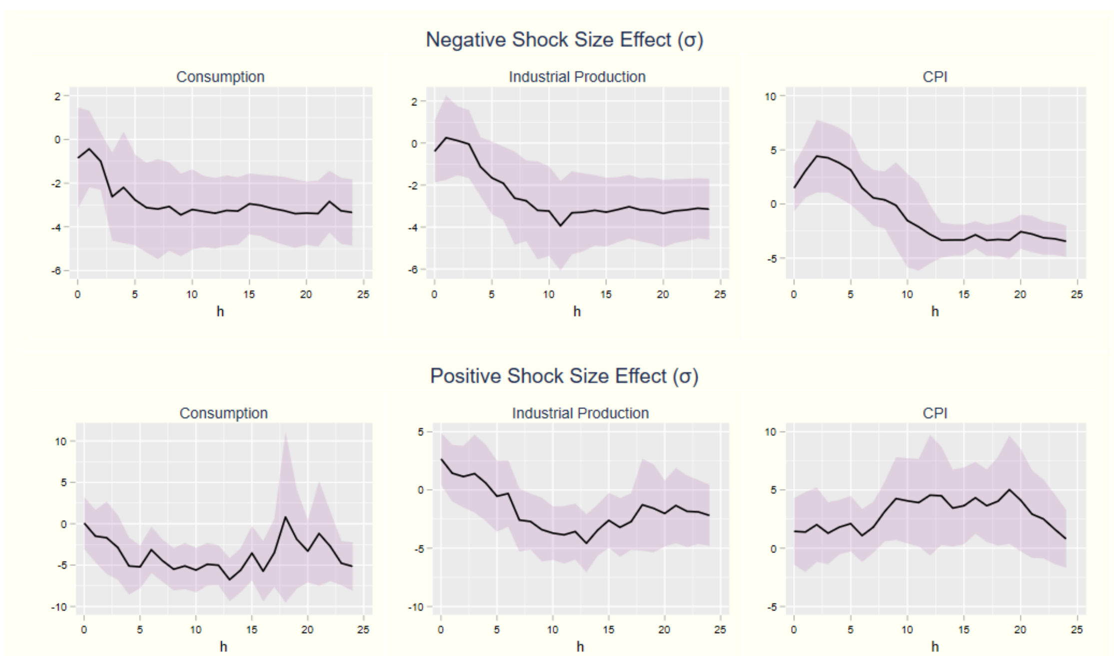

Figure 1

Big cuts yield proportionally smaller values of all of our variables of interest in the long-run. The same is true for big hikes relative to small hikes with the exception for inflation, where it appears that the conventional relationship between output and inflation is weakened for larger changes. All confidence bands are plotted at a 90% interval as standard in this literature (e.g., Angrist et al., 2016) and the plots in levels can be found in the appendix, though the most clear interpretation of these results is compiled in Table 1.

We can also see if positive and negative shocks produce mirroring effects (sign effects). Figure 2 shows that while for small shocks not much can be said, the asymmetry does kick in for large chocks.

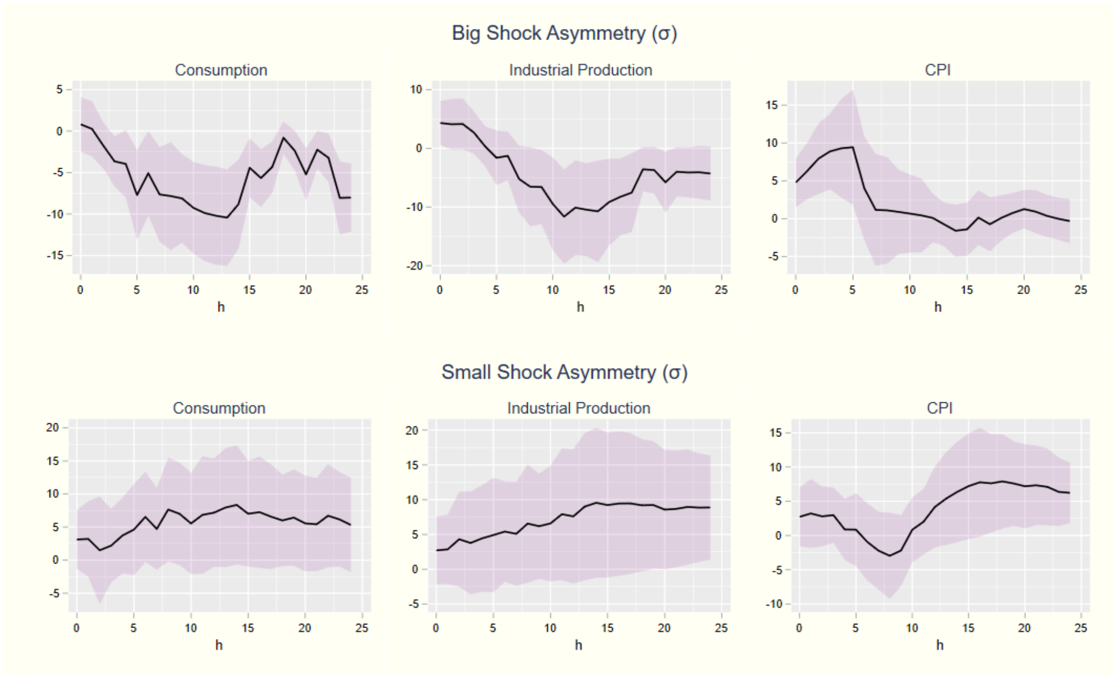

Figure 2

Specifically, these figures are produced by looking at the sum of the cut and hike coefficients and normalizing by the standard deviation of the hike (since that's the default estimate). One disadvantage of this approach is we cannot extrapolate what's driving these graphs, though the size effect graphs provide a good frame of reference. Looking at the graphs in levels confirms that intuition: the asymmetry for consumption and industrial production for big shocks is a consequence of the more pronounced effects during hikes. For inflation, the asymmetry seems to disappear at a long horizon, but at short horizon the significant estimates is because of the relatively weaker effect of hikes on inflation. Overall, this provides some evidence for the literature that has found fundamental differences between the transmission of expansionary and contractionary monetary policy.

In general, I find these results are not sensitive to perturbations in lag length choice, variable selection, and also different parametric approaches that will be detailed later.

Non-Parametric

In a vacuum, parametric approaches are more desirable for these settings, if nothing else for computational reasons. Unfortunately, the parametric approach I have the most baseline confidence in does not allow for the estimated effects to be state-dependent. State-dependent effects means that we want our shock response parameter to potentially differ at any given point in time based on the realizations of certain control variables (or indicator functions of control variables). Informally, when we simply include controls in a specification, this "demeaning" occurs for realizations over the entire time series for all controls, rather than a subset of them at each t. Per Jordà (2023), state-dependent LP requires that for each control variable, even those we don't want to include for state-dependence, we need an interaction term with what we are instrumenting. Given that at a minimum we need to include lagged outcome and control variables with a healthy number of lags (Plagborg-Møller and Montiel Olea, 2021), this creates an infeasible number of instruments for LP-IV. Further, Gonçalves et al. (2024) shows excluding these terms would induce significant bias when considering large shock sizes. This is because the states of the world we are interested in are not exogenous processes[5], so their recommendation of a non-parametric approach is a logical pairing with our LP-IV default.

Some extremely preliminary non-parametric estimation results have confirmed what was found in the parametric approach. However, to get a sense of precision, one needs to bootstrap the standard errors, which means this procedure will take much more time. Further, we will need to impose some structural restrictions (e.g., additivity) to deal with the curse of dimensionality. At a minimum, it is not feasible to include all the controls (including lags) of the parametric estimation. One thing this complexity can potentially buy, however, is the ability to make comparisons across regressions. For our parametric approach, we compare big to small coefficients in the same estimation. With a bootstrap approach unavoidable here, we can also see how fundamentally different our estimates are to a specification that restricts nonlinearities by bootstrapping the variance of difference in different coefficients.

Ancillary Exercises

It's vital for this project to bear fruit for there to be confidence in the "fact finding" mission itself. It's therefore reasonable to consider many different parametric approaches to determine how sensitive the results are to other common specifications. For this, we will also consider different versions of LP, various VAR setups, and Bayesian extensions of both. What has been done so far only relates to LP. In the appendix, I show the base LPs for different monetary shock series. Another exercise is incorporating state dependence. Jordà (2023) shows state-dependence can be accounted for by including interaction terms with shocks and controls. In doing this exercise, I find that it

[5] Whereas our regime decomposition decomposes a noise process into several, see appendix

yields fundamentally the same results as the baseline LP-IV. But because of the previously referenced issues from plugging in shock series directly into a LP, the non-parametric approach is still a necessary complement.

Future Work and Conclusion

The plan for the future is to continue to gather more empirical results to assess the sensitivity of the LP-IV approach and also to see how well an off-the-shelf model that allows for price setting asymmetry can account for our findings. Aruoba et al. (2017) does a Bayesian estimation of a New Keynesian model with monetary policy shocks and the downward rigidity structure of Kim and Ruge-Murcia (2009) but do not provide impulses responses. Currently, I am trying to make that extension, but progress has been complicated by the errors in the publicly available code. Further, it is difficult to estimate these impulse responses as well without violating Jensen's inequality. If we assume agents do not expect and further shocks, there are no issues, but we would expect empirical impulse responses to better mirror the cases where people think there may be shocks but they do not occur. So far, I have not found any applications of Matlab's symbolic toolbox and a second order approximation for this case. For now, I am ignoring the Jensen's inequality issue and just trying to get a handle on the most simple case.

On a broader level, time will also be spent more directly motivating the importance of these findings. Of course, it's likely that these results distort what people are estimating to be optimal policy, but it would be better to connect these findings into a seperate, deeper issue people are studying. Further, even looking at the optimal policy question itself is not as straightforward. For instance, Lee (2023) suggests that "gradual steps" in monetary policy may be advisable since big changes are proportionally less effective. But this prescription does not account for forward guidance or anticipation effects, and Stein and Sunderam (2018) presents compelling theoretical evidence that gradualism is not possible without forward guidance. Overall, there are lots of interesting questions still left unsettled nonlinearities can potentially provide important context for.

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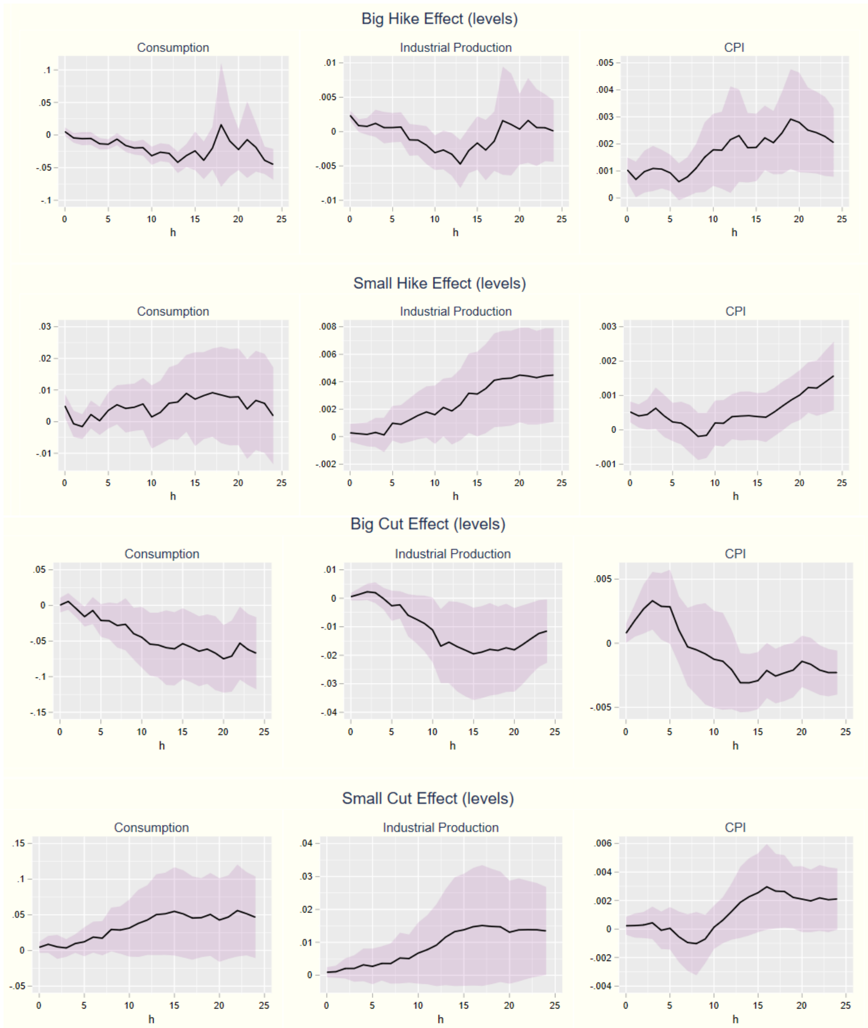
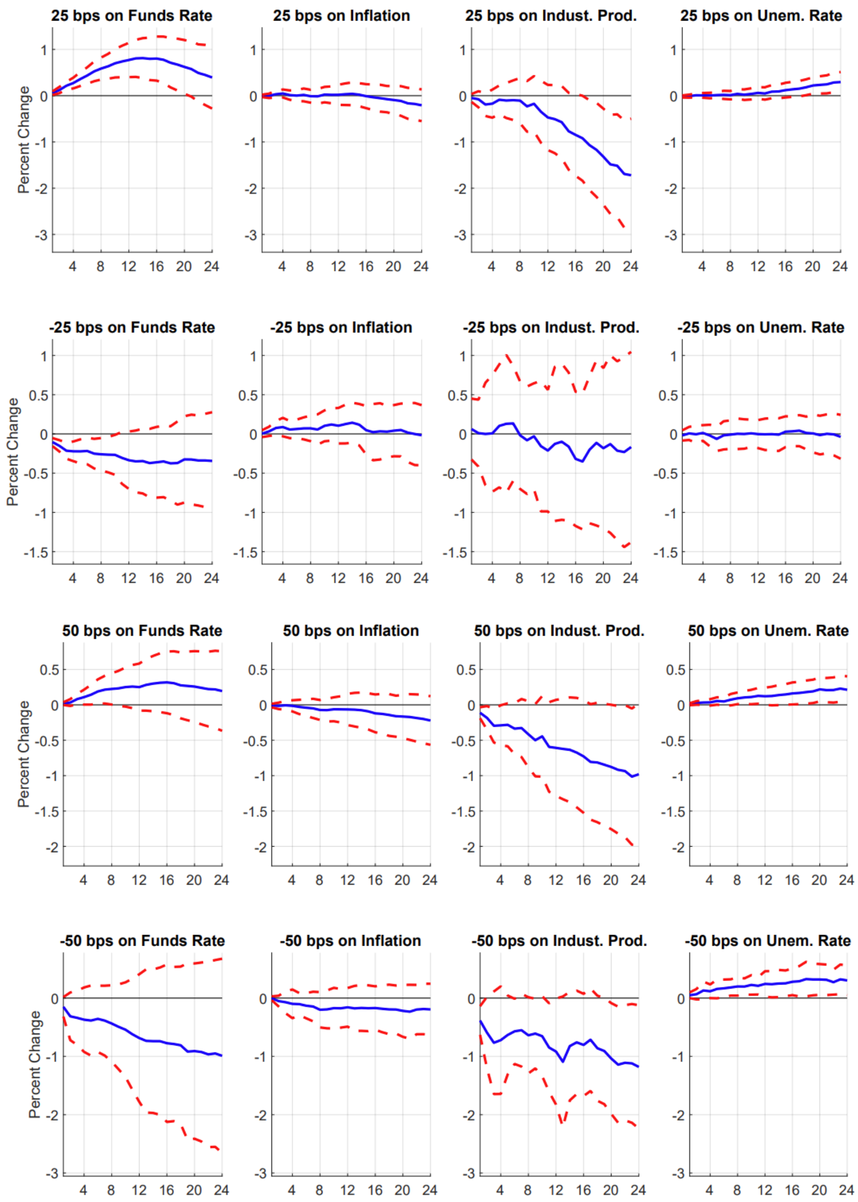
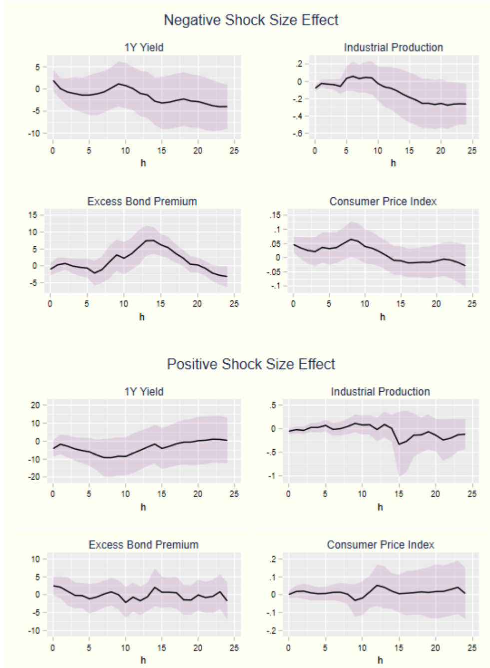
Appendix



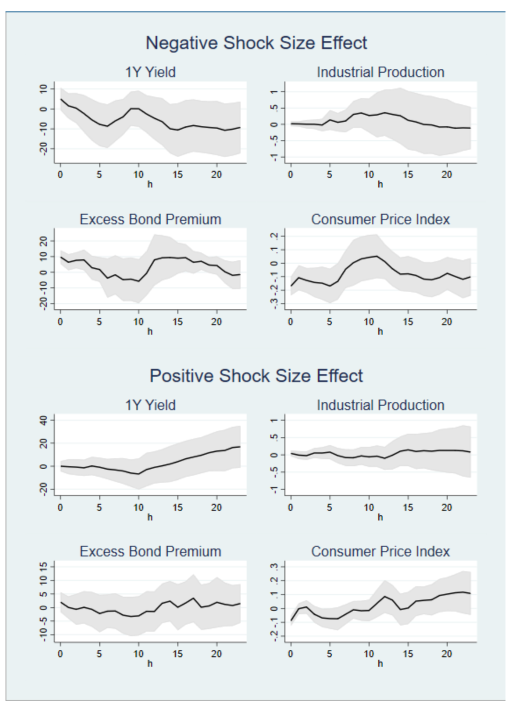
Estimation in levels



Extension of Angrist et al. (2016) to 50 basis points



LP with Bauer and Swanson (2023)



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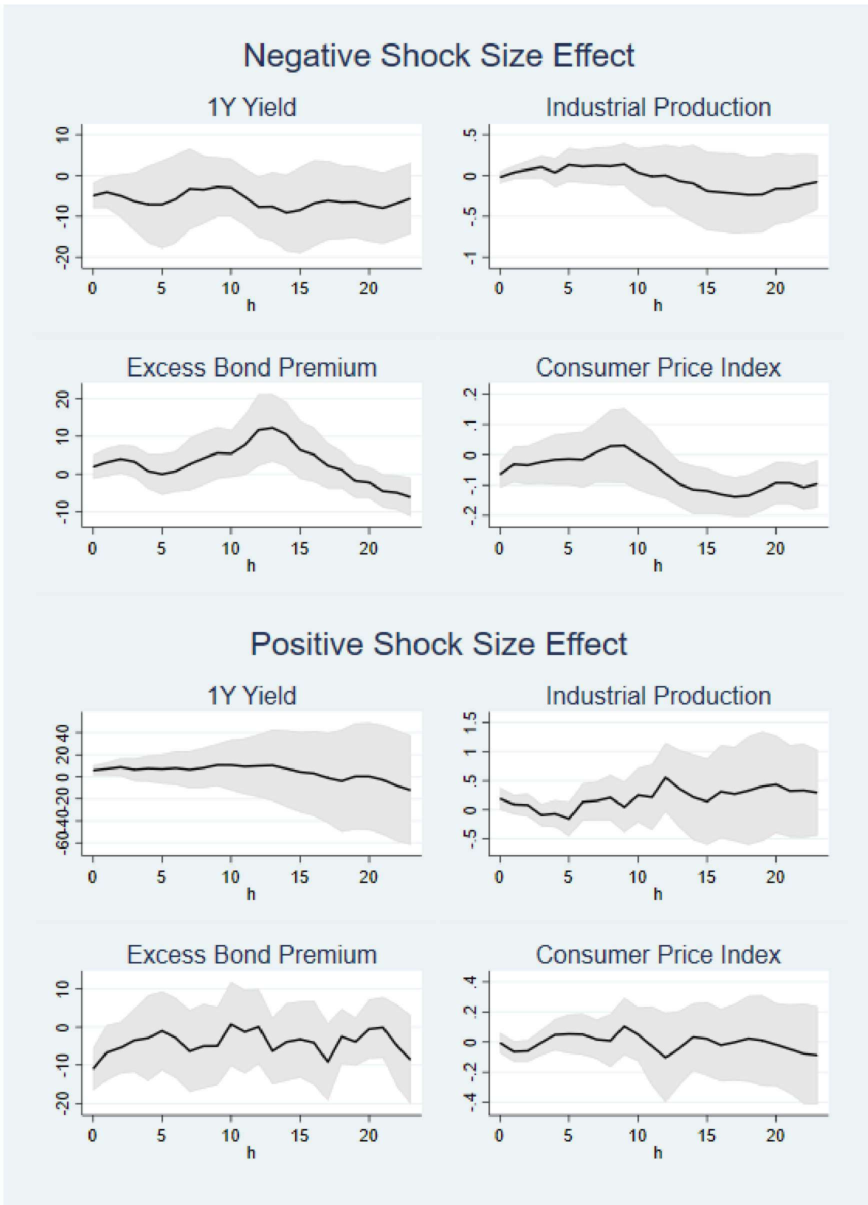
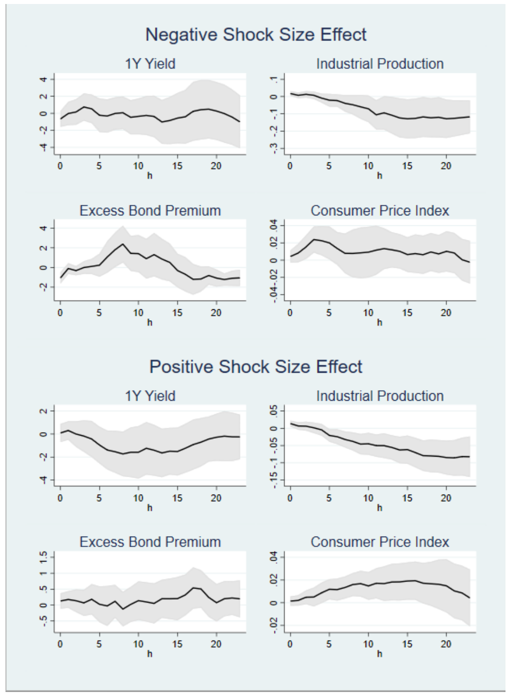
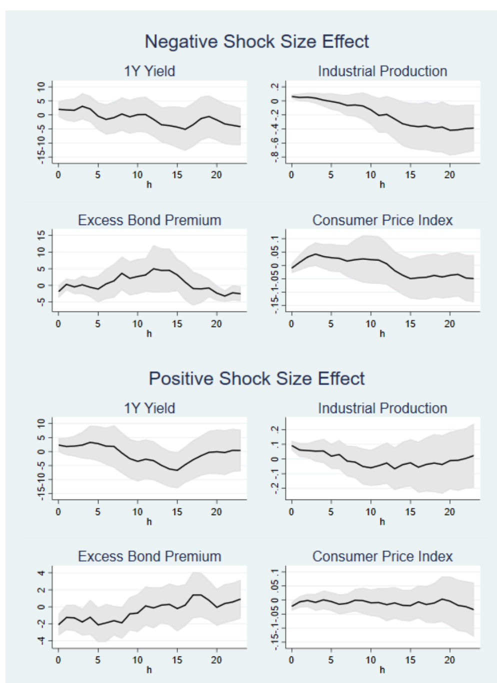


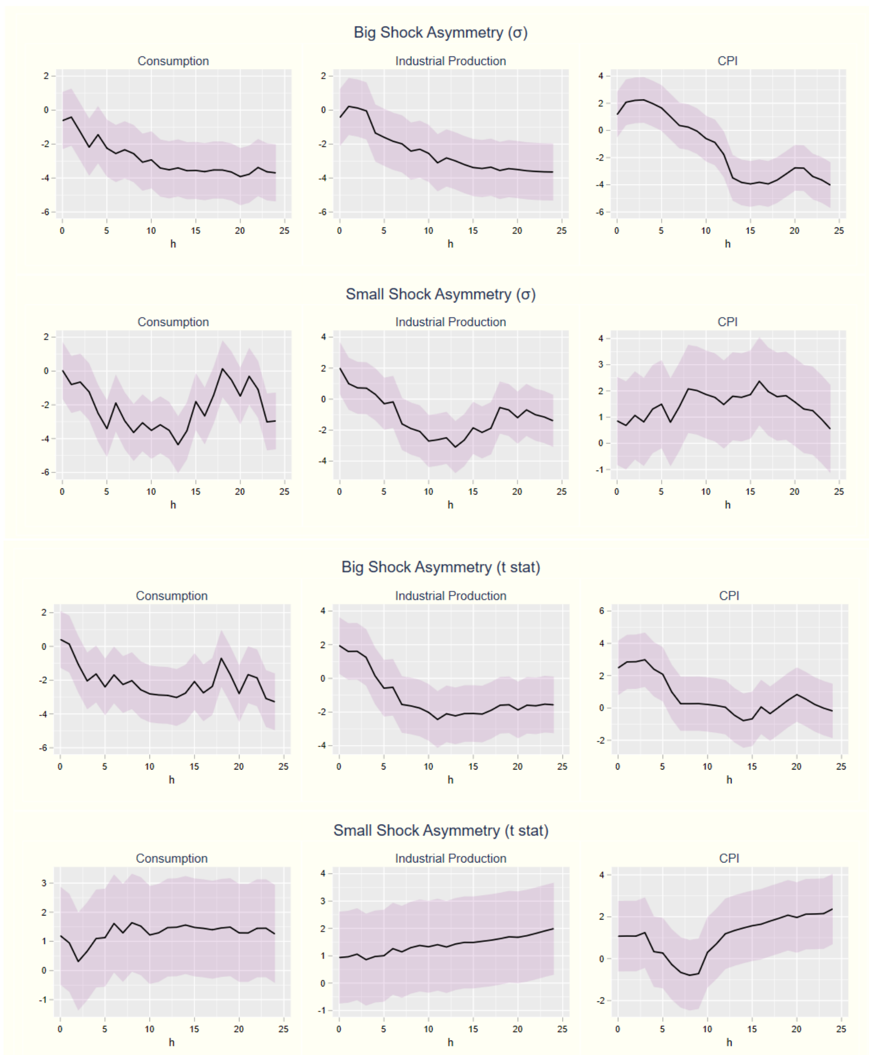
LP with Nakamura and Steinsson (2018)



LP with Romer and Romer (2004)



LP with Aruoba and Drechsel (2023)



t-statistics for sign and size effects