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MONETARY POLICY UNDER UNCERTAINTY AND LEARNING: AN OVERVIEW

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MONETARY POLICY UNDER UNCERTAINTY AND LEARNING: AN OVERVIEW

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Resumen

Todo banco central debe tomar sus decisiones de política en medio de un escenario incierto, basándose en su conocimiento imperfecto y cambiante sobre la economía. Aunque la investigación sobre política monetaria con incertidumbre y aprendizaje ha encontrado pocos resultados generales, una lección contundente es que no se puede pasar por alto ni una ni otro. Este artículo hace una revisión selectiva de la literatura existente sobre la incertidumbre y el aprendizaje, con énfasis en lo que atañe a la conducción de la política monetaria. Luego analiza la investigación de frontera presentada en la última conferencia anual del Banco Central de Chile, que reúne nuevos resultados teóricos y evidencia empírica válida tanto para países desarrollados como para la economía chilena.

Abstract

Central banks must make policy decisions in the face of uncertainty based on imperfect and evolving knowledge about the economy. While few general results have emerged from the research on monetary policy in the face of uncertainty and learning, a key lesson is that neither uncertainty nor learning can be ignored. This paper selectively reviews the literature on uncertainty and learning, specifically on the insights that are important for the conduct of monetary policy. Then it surveys the new research presented at the latest annual conference of the Central Bank of Chile, which uncovered recent theoretical results and empirical evidence for developed countries and the Chilean economy.

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"Uncertainty is not just an important feature of the monetary policy landscape: it is the defining characteristic of that landscape," Alan Greenspan (2003).

1. INTRODUCTION

Central bank economists and academic economists conducting research on the design of monetary policy have made significant advances in recent years. This work has led to a clearer understanding of the desirable properties of interest rate rules, the role of announcements and communication, and the consequences of inflation targeting for both inflation and the real economy. Dynamic stochastic general equilibrium (DSGE) models have been extended from the small scale and often calibrated versions initially employed to address policy issues to much larger models that are estimated using Bayesian techniques. These models are now used by many central banks for policy evaluation.[1] However, much of this work neglects one of the key issues that policymaker face – the pervasive role of uncertainty.

The huge swings in oil, food, and other commodity prices observed in recent years, and the dramatic global financial crisis dominated discussions of monetary policy during the past year and provide vivid reminders of how uncertainty, imperfect knowledge of the economy, and the need to learn how new developments in world goods and financial markets affect the macro economy and influence the conduct of monetary policy. In this volume, leading international scholars address many of the key issues relevant for central banks who must by necessity operate in environments of uncertainty, and in which policy makers and the public are continually learning about the economy.

In the following section, we selectively review the literature on uncertainty and learning, focusing specifically on the insights that are important for the conduct of monetary policy. We then survey the new research presented in the Central Bank of Chile's Annual Conference of 2007 and contained in the Volume XIII of the Series on Central Banking, Analysis, and Economic Policies, edited by Klaus Schmidt-Hebbel and Carl. E. Walsh (2009).

2. TYPES OF UNCERTAINTY AND THEIR IMPLICATIONS FOR MONETARY POLICY

Limitations of economic theory and data, structural changes in the economy, the inherent unobservability of important macroeconomic variables such as potential output and the neutral rate of interest, as well as disagreements over the correct model of the economy and the transmission process of policy, are just some of the reasons why central bankers operate in an environment of uncertainty. Research into the effects of uncertainty, and the design of optimal policy in the face of uncertainty, have, in broad terms, focused on three types of uncertainty: additive uncertainty, model uncertainty, and imperfect information.

To illustrate these difference forms of uncertainty, suppose that the "true" model of the economy takes the form

$$\mathbf{y}(t+1) = \mathbf{A}\mathbf{y}(t) + \mathbf{B}\mathbf{y}(t \mid t) + \mathbf{C}i(t) + \mathbf{D}\mathbf{u}(t+1) \tag{1}$$

where $\mathbf{y}(t)$ is a vector of macroeconomic variables at time t, $\mathbf{y}(t|t)$ is the policy maker's current estimate of $\mathbf{y}(t)$, $i(t)$ is the central bank's instrument, $\mathbf{u}(t)$ is a vector of random, exogenous disturbances, and $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$,and $\mathbf{D}$ are matrices containing the parameters of the model. Most models used for monetary policy analysis can be represented by this linear structure.

Additive uncertainty is represented by the disturbances $\mathbf{u}(t+1)$: when setting its instrument at time t, the central bank does not know what future shocks $\mathbf{u}(t+1)$ will hit the economy. Model uncertainty arises because the central bank does not know the true parameters that characterize the model (the values of $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$, and $\mathbf{D}$); parameter estimates are subject to error, and the policy maker may believe some parameters are zero when they are in fact non-zero. Finally, imperfect information arises because the actual value of $\mathbf{y}(t)$ may be unobserved or only observed with error due to measurement error or data lags; as a consequence, the policy maker's best estimate of $\mathbf{y}(t)$, $\mathbf{y}(t|t)$, may be wrong. Each of these sources of uncertainty will be discussed in turn.

[1] See Galí (2008) for an excellent treatment of the basic new Keynesian model that has become standard in monetary policy analysis. Examples of estimated DSGE models include Christiano, Eichenbaum, and Evans (2005), Levin, Onatski, Williams, and Williams (2005), Smets and Wouters (2003), Adolfson et al (2007), and Christiano, Motto, and Rostagna (2007).

1.1 Additive uncertainty

The most extensively studied form of uncertainty is that arising from additive errors to the model's structural equations. In terms of the notation in equation (1), additive uncertainty is represented by $\mathbf{Du}(t+1)$. At the time the central bank must make its policy choice, the value of this term is unknown. Uncertainty about the realized values that $\mathbf{Du}(t+1)$ will take on is the only form of uncertainty that typically is included in most models. Modern DSGE models often include random disturbances that enter the equilibrium conditions in non-linear ways, but these models are then linearized, so that disturbances appear as additive error terms.

The problem of characterizing optimal policy in the face of additive uncertainty is well understood when the objectives of the policy maker can be expressed as a quadratic function of various target variables. The standard assumption that central banks desire to minimize the volatility of inflation around its target and real output around potential output lends itself naturally to a representation in terms of a quadratic loss function in which squared deviations of inflation from target and output from potential are penalized. The combination of linear, additive disturbances and quadratic objectives satisfies the well-known principle of certainty equivalence–all that matters for optimal policy are the expected values of the unknowns. Simply replace unknown disturbances with one's best forecast of their values and then treat these forecasts as if they were known with certainty. Thus, again in terms of equation (1), the central bank would replace $\mathbf{Du}(t+1)$ with its expected value, $\mathbf{D}E\mathbf{u}(t+1)$ and then choose policy as if the true model were known with certainty to be

$$\mathbf{y}(t+1) = \mathbf{Ay}(t) + \mathbf{By}(t \mid t) + \mathbf{C}i(t) + \mathbf{D}E\mathbf{u}(t+1) \tag{2}$$

In this case, optimal policy does not require knowledge of the variances of the disturbances or the co-variances among the different disturbances. This does not mean that *only* the expected value of the disturbance is relevant. Policy makers will usually need to forecast future values of these exogenous disturbances and this will require some knowledge of, or at least assumptions about, the persistence of shocks. For example, a forecast that the price of oil will rise is generally not sufficient; the policy maker will need to forecast whether the rise is temporary or whether it is likely to be persistent.

To deal with additive uncertainty, Giannoni and Woodford (2002) have proposed optimal policies, policies they call *robustly optimal policies*. Robustly optimal policy rules describe how the policy instrument should be set solely in terms of the macroeconomic variables that define the central bank's objective. If the central bank is concerned about maintaining low and stable inflation, stabilizing a measure of output relative to potential (the output gap), and stabilizing interest rate volatility, then the robustly optimal policy rule would show how the policy interest rate should be set as a function of inflation, the output gap, and lagged interest rates. Thus, implementing such a policy does not require information about the time series properties of the exogenous disturbances. Such a property is desirable, as it may be difficult to accurately forecast the degree of persistence in exogenous economic disturbances.

When the central bank is concerned with inflation and output gap stability, the optimal rule can be defined in terms solely of inflation and the output gap. In fact, the optimal policy can be characterized in a simple way – keep a specific linear combination of inflation (relative to target) and the output equal to zero. If inflation is above target, then the output gap should be negative. The Bank of Norway, for example, describes the desirable properties of an interest rate path as one that ensures that the output gap is negative if the inflation gap – inflation relative to target is positive. Adjusting the policy interest rate to maintain this sort of relationship between inflation and the output gap is often called a targeting rule, as it just involves the variables that are directly part of the central bank's objectives.

Unfortunately, robustly optimal policy rules generally require the central bank to form forecasts of inflation and the output gap. Because monetary policy affects the economy with significant lags, policy must be forward looking, and this forces the central bank to rely on forecasts. But to form forecasts of future inflation or real economic activity, the policy maker will need to decide whether a shock such as an oil price increase is temporary and will be reversed or is permanent. Thus, robustly optimal rules do not actually eliminate the need to forecast future disturbances.

In contrast to a robustly optimal rule, central bank behavior is often represented by simple instrument rules such as a Taylor rule. These rules typically assume monetary policy is adjusted in a systematic manner in response to current movements in inflation and measures of the output gap. Sometimes other variables, such as the exchange rate, are also included. Given a specification of the central bank's objective, the coefficients in the rule can be chosen optimally. In contrast to fully optimal rules such as Giannoni and Woodford's robustly optimal rules, the best response coefficients in simple Taylor-type rules will depend on the relative variances of the basic disturbances that affect the economy. Thus, to design the optimal "simple" rule requires a great deal of information about the additive shocks that hit the economy.

1.2 Model uncertainty

Model uncertainty encompasses a wide range of potential sources of error. Model misspecification, parameter uncertainty, and estimation error can all be grouped under this heading. Uncertainty about the values of the coefficient matrices **A**, **B**, **C**, and **D** is one reflection of model uncertainty. This uncertainty may arise because the central bank does not know the true values of the parameters in the model and must estimate them, or it could arise because the central bank's model incorporates incorrect assumptions about how the macroeconomic variables are related. Or the true model may be evolving over time in unknown ways due to technological changes and innovations.

To illustrate how model uncertain affects the policy problem, suppose that we can ignore imperfect information (so that $\mathbf{y}(t) = \mathbf{y}(t \mid t)$), let $\mathbf{A} + \mathbf{B} = \mathbf{H}$, and to keep the example simple, assume only elements of **A** and **B** are not known with certainty. Then the model becomes

$$\mathbf{y}\left(t+1\right) = \widehat{\mathbf{H}}\mathbf{y}\left(t\right) + \mathbf{C}i\left(t\right) + \mathbf{v}(t+1) \tag{3}$$

where $\mathbf{v}(t+1) = \mathbf{D}\mathbf{u}\left(t+1\right) + \left(\mathbf{H} - \widehat{\mathbf{H}}\right)\mathbf{y}\left(t\right)$ and $\widehat{\mathbf{H}}$ is the central bank's estimate of **H**. Errors in estimating **H** now become part of the error term of the equation, but the key difference from the case of additive uncertainty is that the errors represented by $\mathbf{v}(t+1)$ are now correlated with the endogenous variables $\mathbf{y}(t)$. The disturbance terms are no longer exogenous; misspecification is correlated with the macro outcomes. This has important implications for policy choice, as first pointed out by Brainard (1967).

The type of uncertainty represented in (3) is called multiplicative uncertainty, since the uncertainty associated with the parameters in H multiply the endogenous variables. In the example he considered, Brainard (1967) showed that multiplicative uncertainty would make optimal policy less activist. Alan Blinder famously characterized the first step in a preemptive policy for controlling inflation as requiring the central bank to "Estimate how much you need to tighten or loosen policy to 'get it right', then do less" (Blinder 1998, p. 17). This statement accurately reflected the caution that Brainard found to be appropriate when faced with multiplicative uncertainty.

In research subsequent to the work of Brainard, it was found that caution is not necessarily the best response to model uncertainty (Craine 1979, Giannoni 2002, Soderstrom 2002). In fact, some forms of multiplicative uncertainty can call for a more robust response than otherwise. For example, this can be the case when the uncertainty is about the dynamic response of the economy to shocks. If the central bank is uncertain about the degree to which current inflation may influence future inflation, it may be best to respond strongly to ensure current inflation remains stable. Thus, an aggressive policy rather than a cautious one may be the best policy. In general, economists have found that there are no clear guidelines about how best to react when faced with this type of uncertainty.

Multiplicative uncertainty is certainly not the only form, nor necessarily the most important form of model uncertainty. More commonly, there are competing models for how the economy operates and how monetary policy affects macroeconomic activity and inflation. Within current macroeconomic circles, there are economists who employ models in which monetary policy can have important short-run real effects due to sticky prices and wages and other economists who use models in which monetary policy is impotent in affecting the real economy because all wages and prices are flexible. Faced with these competing models in an environment in which no one knows the true model of the economy, how should policy makers behave?

Clearly, policy is unlikely to contribute to macroeconomic stability if policy makers hold beliefs about the economy that are wrong. Romer and Romer (2002) attribute policy mistakes in the U.S. during the late 1960s and the 1970s to the use of a wrong model. Specifically, they argue that policy makers during the 1960s believed there was a permanent tradeoff between average unemployment and average inflation. This led, in the view of Romer and Romer, to the onset of the Great Inflation in the U.S. They then argue that once inflation had reached high levels, policy makers came to believe that inflation was insensitive to recessions, implying the cost of reducing inflation would be extremely high. Thus, inflation was allowed to rise and policy makers delayed reducing it because they based decisions on models that we now view as incorrect.

The example of model uncertainty provided by (3) showed how errors in the central bank's estimate of the parameters in **H** would interact with the endogenous variables represented by $\mathbf{y}(t)$. But if $\mathbf{H} - \widehat{\mathbf{H}}$ reflects estimation error or purely random fluctuations in the elements of **H**, it at least might not be systematically related to economic developments. Hansen and Sargent (2003, 2004) have studied optimal policy in environments where the model uncertainty faced by the policy maker is not exogenous but is “designed” to be particularly troublesome. They consider the case in which the policy maker fears that model misspecification will yield what, from the policy maker’s perspective, is the worst possible outcome. In this environment, the policy maker seeks policies that are robust in the sense that they lead to reasonable outcomes even in the worst case scenario. In the context of a simple monetary policy problem, Walsh (2006) shows that the worst case scenario for the central bank involves the occurrence of a positive inflation shock at the same time the economy is already in a recession. Such a scenario pushes the economy further away from the objectives of both low inflation and full employment.

Optimal policy in the face of this malicious mis-specification turns out to require the central bank to employ a model of the economy that is deliberately distorted in the sense that the central bank should assume inflation shocks will be much more persistent than they are actually expected to be. Thus, in contrast to the Gianonni and Woodford (2002) approach, which designed policy rules that did not require the central bank to actually know (or even estimate) the true persistence of inflation shocks, the Hansen and Sargent approach has the central bank behave as if inflation shocks were always very persistent, even if they generally aren’t.

Worst case scenarios are, almost by definition, events that occur with low probability, and the Hansen-Sargent approach has been criticized for putting too much weight on the worst case scenario in policy decisions. However, the idea that a policy maker might want to use a distorted model when designing policy is supported by other lines of research. For example, Levin and Williams (2003) consider what happens when a policy is designed to be optimal for a particular model, but that model turns out to be wrong. They find that policy rules designed to be optimal in models that display high levels of inertia also perform well if the “true” model of the economy is very forward looking. Unfortunately, they found the converse not to be true. Policies designed to do well if forward-looking behavior is important often perform disastrously if the actual economy displays high degrees of inertia. Hence, even if the central bank believes inflation and real economic activity are heavily influenced by expectations of future inflation and growth, it might still want to act as if the economy were much more backward looking.

In practice, central banks often deal with model uncertainty by employing several models of the economy, using the different models to cross-check forecasts and to ensure that policies are not excessively sensitive to assuming a particular model is correct. Faced with competing models of the economy, a sensible approach might be to evaluate alternative polices in several models and to weight the different models based on an assessment of their likelihood. However, Cogley, Colacito, and Sargent (2007) have illustrated how model uncertainty can lead to bad policies even when the policy maker is carefully trying to account for the uncertainty by using multiple models to evaluate policies. They consider two simple models. One model, labeled the Samuelson-Solow model, implies the central bank faces a tradeoff between average unemployment and average inflation. The other incorporates the natural rate hypothesis, implying no tradeoff between average inflation and unemployment. This second model also implies that a credible disinflation would reduce inflation costlessly. The policy maker assigns probabilities to each model, reflecting the likelihood the data assign to each model being the true model. Cogley, Colacito, and Sargent show that by the early 1970s, U.S. data implied that almost all weight should be placed on the natural rate model. In turn, this meant that the optimal policy would be to immediately bring down inflation. However, the data still assigned a small but positive probability that the Samuelson-Solow model might be correct, and if that model turned out to be true, the output costs of an immediate disinflation would be enormous. So even though the central bank is almost certain the natural rate model is correct, it fails to reduce inflation out of fear that the Samuelson-Solow model might be correct. Thus, even a model the data suggests is unlikely to be true can affect policy choices when the policy maker employs several models as a means of seeking robust policies.

1.3 Imperfect information

A final type of uncertainty arises from imperfect information. Just about any form of uncertainty could be labeled as due to imperfect information (about the realizations of the additive disturbances, about the true model, etc.). However, we will use it to refer to a specific aspect of uncertainty – that due to the inability to perfectly observe the current state of the economy and/or macroeconomic variables that are critical for policy design.

Policy decisions are made based on noisy and imperfect data about the economy. A number of authors have investigated how data uncertainty affects optimal policy. Intuitively, one would expect that the presence of noise in macroeconomic data would call for responding less strongly to new data. Responding too strongly might end up simply introducing volatility if the signal to noise ratio is small, i.e., if much of the variation in the data is simply noise. Rudebusch (2001) studied how data noise would reduce the optimal responses to inflation and the output gap in a standard Taylor rule. Earlier work, ignoring data uncertainty, had found that the optimal response to the output gap was much larger than Taylor had found for the Federal Reserve under Alan Greenspan. Rudebusch attributed part of the weaker response found in the data to be the presence of noise in measures of the output gap.

Besides the issue of pure measurement error in real time data on observable variables, a further difficulty arises from the fact that many of the variables that play critical roles in theoretical models are, in fact, not directly observed. The output gap is the best example of this problem. New Keynesian models define the output gap as the percentage difference between actual output and the output the economy would produce if all wages and prices were flexible, the so-called flexible-price output level. While data on actual output is subject to measurement error and data revisions, it is at least directly measurable. The same cannot be said of the flexible-price output level. Any estimate of this output level will be dependent on a particular theoretical model of how the economy would behave with flexible prices. Older definitions of the output gap that measured output relative to potential output also suffered from similar problems. Potential output is not observed but must be estimated, and standard techniques typically relied on simple statistical methods to equate potential output with trend output. This still left open the issue of how best to estimate the trend growth rate of real output.

Inevitably, measures of trend output are backward looking. They use historical data to estimate trends. This means they are likely to have difficulty in picking up shifts in underlying growth trends. A case in point was the 1970s, when many countries experienced a decline in trend growth. Orphanides (2002) has argued that bad macroeconomic policies during the 1970s in the U. S. resulted from the failure to recognize this decline in the trend rate of growth. By basing its estimate of trend growth on historical data, the Federal Reserve was slow to pick up the decline in the growth rate and so it overestimated the path of trend output in the 1970s. As a consequence of overestimating trend output, the Federal Reserve believed a negative output gap was opening up. In the face of this development, the Fed adopted policies that, in retrospect, were too expansionary. This data-uncertainty hypothesis represents an alternative explanation for the 1970s'Great Inflation to the one highlighted by the above mentioned model-uncertainty hypothesis.

Because of the difficulties involved in measuring the output gap, McCallum (2001) has argued that central banks should not react strongly to it. Alternatively, Orphanides and Williams (2002) have found that policy rules that respond to the *change* in the estimated output gap often perform well and avoid some of the measurement problems that make it difficult to estimate the *level* of potential output.

Problems with estimating the output gap are only one example of how key variables that modern economic theory suggests should be central to monetary policy are difficult to estimate and may even be unobservable. Another example is the neutral real interest rate, defined as the real interest rate consistent with a zero output gap and a zero deviation of inflation from target. Some modern models imply that the actual real interest rate should move in parallel with this neutral real rate, but of course the neutral real rate is unobservable. Several authors have attempted to estimate the neutral real rate and the output gap (see Kuttner 1994, Laubach and Williams 2003, Garnier and Wilhelmsen 2005, and Benati and Vitale 2007), but such estimates generally rely on restrictions implied by a particular model of the economy. So if policy makers are uncertain about the correct model, they will also be uncertain about how best to measure the neutral real rate and the output gap. Thus, imperfect information is a major problem facing policy makers.

1.4 Learning

The uncertainty faced by central banks reflects, in large part, our imperfect understanding of macroeconomics. Because our understanding is imperfect, economists and policy makers are constantly engaged in a process of learning about the economy. Similarly, members of the public are forming expectations based on their evolving understanding of the economy and of policy maker's behavior. Consequently, learning is pervasive – models are constantly refined and re-estimated, new models are developed to reflect the latest progress in economic research, and previously ignored factors suddenly become important and must be incorporated into policy models. At the same time, the public must assess policy decisions and attempt to learn about the objectives of the central banks and the way policy is being carried out. In recent years, a large literature has developed that investigates the effects of learning on macroeconomic outcomes and its implications for monetary policy.

Much of the work on learning in macroeconomics is based on the book by Evans and Honkapohja (2001). Evans and Honkaphoja provide an excellent overview of this research and its implications for monetary policy. The literature they survey drops the extreme informational assumptions implicit in the rational expectations approach. Instead, individuals (and policy makers) are viewed essentially as econometricians, using the latest data to re-estimate and update their models and then using these models to make forecasts of future inflation and other macroeconomic variables. Evans and Honkaphoja argue that this view of learning reflects the "principle of cognitive consistency," in that it assumes private "agents should be about as smart as (good) economists".

By incorporating learning explicitly, two general issues of relevance for policy can be studied.

First, will the economy under learning converge to the equilibrium consistent with rational expectations? And second, how are macroeconomic dynamics affected by learning?

If rational expectations equilibria are not stable under learning – a property called e-stability or learnability – than the properties of the rational expectations equilibrium becomes irrelevant as a way to describe the economy's behavior once the economy's structure is understood. The standard practice in policy analysis is to study the properties of alternative policies under the assumption that the private sector fully understands how the central bank is behaving. In terms of the eventual behavior of the economy, this may be an appropriate assumption, but only if the public eventually learns the true structure of the economy. And if the public learns gradually about the different policies the central bank might follow, the economy may not converge to the rational expectations equilibrium.

As Evans and Honkaphoja (2001) discuss in their overview chapter, some policy rules for the central bank that appear to be quite reasonable rules under rational expectations can lead to instability under quite reasonable models of learning. However, Bullard and Mitra (2002) show that when the central bank follows a simple Taylor rule for setting the nominal rate of interest, the same condition that ensures a unique equilibrium under rational expectations also ensures that the equilibrium is stable under learning. This condition, called the Taylor Principle, requires the central bank to adjust the nominal rate more than one-for-one with inflation.[2] However, Bullard and Mitra also show that if the central bank responds to expected future inflation rather than current inflation, some policy rules that lead to indeterminacy (multiple equilibria) under rational expectations have equilibria that are stable under learning. In general, Evans and Honkaphoja argue that expectational-based policy rules – rules in which the central bank responds to the private sector's inflation expectations and the output gap – have desirable properties. These rules implicitly incorporate the public's learning into the policy rule.

The second broad arena in which the learning literature has contributed to our understanding is in the area of macroeconomic dynamics. The manner in which the economy evolves will depend on the way the public learns, and the response of the economy to disturbances can differ significantly in the presence of learning from what would occur under rational expectations. Incorporating the effects of learning can be particularly important if the central bank is considering changing its policy behavior. The private sector's attempts to learn the new policy can affect the economy's adjustment if the central bank is not explicit or transparent about its policy. For example, Erceg and Levin (2003) studied the role of learning in accounting for the steep recessions in the U.S. associated with the Volcker disinflation of the early 1980s. Under rational expectations, an announced reduction in the Fed's inflation target should have lowered inflation with little loss in real output. By assuming the Fed's anti-inflation stance lacked credibility and the public engaged in a process of learning about the Fed's target, Erceg and Levin show they can do a better job of matching the historical experience of a gradual disinflation accompanied by recession.

The learning literature has also developed new insights that are relevant for the debate over the optimal degree of central bank transparency. In general, greater transparency helps speed learning by providing useful information to the public. In that way, transparency can reduce the volatility that can occur when the public is trying to learn the central bank's objectives. Transparency can also ensure the economy converges more quickly to the rational expectations equilibrium (Rudebusch and Williams 2007). Incorporating learning is also relevant for ensuring policies are robust when private agents and the policy maker may have evolving beliefs about the economy, as in Orphanides and Williams (this volume).

Perhaps the most important lesson from the learning literature is that in a world of uncertainty and change, both private economic agents and the central bank engage in learning, and this process of learning cannot be ignored when designing policies to ensure determinacy, stability, and robustness.

1.5 Summary

Central banks must make policy decisions in the face of uncertainty based on imperfect and evolving knowledge about the economy. While few general results have emerged from the research on monetary policy in the face of uncertainty and learning, a key lesson is that neither uncertainty nor learning can be ignored. Policy makers must recognize that situations in which the uncertainty associated with forecasts can be ignored – i.e., when certainty equivalence holds – are unlikely to hold in practice. Accounting for the role of multiple models and seeking policies that are robust across a range of plausible models is important. Seeking robustness may require using models that are distorted in ways that capture if not the worst case scenarios, at least the more threatening ones. Finally, it is critical to recognize the role of data uncertainty, measurement error, and unobservability of key macroeconomic variables in designing and implementing monetary policy.

[2] This condition is weakened slightly if the central bank also responds to the output gap.

2. OVERVIEW OF VOLUME

The essays in this volume offer both theoretical insight and practical guidance to evaluating monetary policy in the presence of uncertainty and the need to learn. Among the general questions addressed are the following: Are there practical means for calculating optimal policies in the face of very general specifications of model uncertainty? Does model uncertainty place limits on the usefulness of optimal control techniques? What types of monetary policy rules ensure stability when private agents employ constant gain learning strategies? How do alternative notions of learning affect the stability of forward-looking models? How are the costs of disinflations affected by the credibility of the central bank's inflation target and the need for the public to engage in learning? How might disinflations affect the structure of the inflation process as private firms update their beliefs about the behavior of inflation, and do these effects alter the relative costs and benefits of announcing a gradual reduction in inflation targets? Are there general rules for formulating models and policy rules that ensure stability when private agents only have lagged data available? Can we develop alternative models, useful for policy analysis, if the effects of monetary policy arise from sticky information rather than sticky wages and prices? Can we estimate unobservable variables that are key for monetary policy decisions using a simple model applied to different countries – and what can we learn about international co-movement and convergence of the latter unobservables and their observable counterparts?

On Chile's monetary policy, this volume addresses the following questions. Did Chile's gradual disinflation experience based on annual targets during 1991-2000 contribute to lower costs of disinflation? How empirically important are additive, model, and information uncertainty? How sensitive is monetary policy to the laws of motion of exogenous shocks and to model misspecification. Finally, how sensitive are boom-bust cycles in Chile to alternative monetary policy rules?

Next we briefly summarize the chapters in this book, referring also to the answers they provide to the above set of questions.

The second chapter in the volume, by George Evans and Seppo Honkapohja, provides an overview of the lessons for monetary policy derived from the growing literature on learning. Evans and Honkapohja have been the leading figures in developing and applying the notions of adaptive learning to macroeconomic issues. In part, their work has been motivated by the idea that economic agents have neither the information nor the information-processing capabilities implicitly assumed by rational expectations approaches. Instead, economists should recognize that individuals are "boundedly rational". One means of operationalizing this notion of bounded rationality is to assume individuals learn adaptively. As the authors note, adaptive learning reflects the way economists typically learn about the empirical structure of the economy – they use new data to update their estimates of the economy's structural relationships or their forecasting equations. Applying this notion of learning to the private sector provides a tractable means of investigating a number of policy-relevant issues without imposing the extreme informational assumptions common to rational expectations models. Using the basic forward-looking new Keynesian model that has become standard in the literature on monetary policy, the authors discuss a number of policy related issues such as determinacy and e-stability under alternative policy rules, imperfect information on current variables, imperfect knowledge of structural parameters, and alternative models of adaptive learning. They also study the implications of learning for understanding hyperinflations and liquidity trap environments.

In their chapter, Lars E.O. Svensson and Noah Williams use a benchmark new Keynesian model to show how policy is affected by the model uncertainty policymakers face. The authors have developed a new methodology for designing optimal monetary policies in the face of model uncertainty. This approach models uncertainty as reflected in shifts in the structural equations that characterize the economy. They represent the economy as jumping randomly between various states. Conditional on each state, the structure of the economy can be described in terms of linear equations and quadratic preferences. Hence, the approach is called a Markov jump-linear-quadratic model. As the authors argue, this approach can be used to model a wide range of types of uncertainty, and, as they assume the current state of the economy is not observable, they discuss the role of learning as well. The fully optimal policy in their framework will involve some experimentation – deliberate policy actions designed to help the central bank better understand the behavior of the economy. Such policies are difficult to calculate, so Svensson and Williams also focus on what they label as *adaptive optimal policies* (AOP). Under these policies, the central bank does not consciously experiment. They find that the gains from experimentation are typically small, a finding consistent with the reluctance of central banks to experiment with the macroeconomy. To illustrate the applicability of their approach to uncertainty, Svensson and Williams employ a small, new Keynesian model that was originally estimated using U.S. data by Lindé (2005). Using this model, the authors compare the AOP policy with optimal policy without learning, that is, when the central bank does not use the new data it receives to update its knowledge about the economy. Besides illustrating the algorithms they have developed to calculate AOP policies, the paper draws a very important policy conclusion – while learning is important for improving the design of policy in the face of uncertainty, the gains from experimentation are small.

Athanasios Orphanides and John Williams study the implications of alternative policies in the face of uncertainty and learning. They employ a small model estimated using U.S. data, but in evaluating monetary policies, they assume the central bank must estimate key macroeconomic variables such as the natural rate of unemployment and the equilibrium real interest rate. Private agents are also uncertain about the structure of the model and employ least squares learning to update their beliefs about the economy. In this environment, the authors show that ignoring uncertainty and learning can be costly – policies that are optimal when uncertainty is ignored lead to poor macroeconomic outcomes when knowledge is imperfect. Policies that are more robust to imperfect knowledge can be obtained if the central bank acts more conservatively in the sense of placing greater weight on inflation objectives relative to stabilizing real economic activity. Interestingly, Orphanides and Williams show that simple policy rules that respond to expected future inflation and either lagged unemployment or the change in the unemployment rate perform well in the face of imperfect knowledge.

George Evans and Seppo Honkapohja examine the behavior of monetary policy rules when the private sector is engaged in learning. A huge literature has examined the implications of simple policy rules, but this work has generally assumed that private agents are fully aware of the rule the central bank is following. If instead members of the private sector must learn about the central bank's behavior, some important new issues arise. One issue relates to the stability of policy rules under different assumptions about the way private agents learn. The standard assumption in the literature on adaptive learning is that, as agents obtain more observations, they place less weight on each one, a learning process known as decreasing gain. An alternative assumption is that agents use constant gain least squares learning in which the weight on new information does not decrease as more observations are accumulated. Constant gain learning may be appropriate when structural shifts might occur, making observations from the distant past less informative. Evans and Honkapohja show that some rules that perform well under decreasing gain learning lead to expectational instability under constant gain learning. Thus, not only is the fact that the private sector is learning important, how they learn is also important. The authors show that policy rules that they describe as expectations-based optimal rules in which the central bank responds to private sector expectations have desirable properties.

Roger Guesnerie considers an approach to learn that differs from the adaptive learning models that have become common in monetary policy analysis. Under adaptive learning, individuals behave much like econometricians, using new observations on macroeconomic conditions to update their estimates of key economic relationships. In contrast to this approach, Guesnerie develops the concept of "eductive" stability. Intuitively, an eductive stable system has the property that if it is common knowledge that the economy is within some neighborhood of the equilibrium, then, regardless of the specific beliefs of individuals, their actions are such that the actual equilibrium is within this neighborhood. Eductive stability can then be thought of as a property of an equilibrium such that, if the beliefs of the agents in the economy are in some region, they will remain within that region under a broad set of updating rules. Thus, eductive stability can be viewed as a necessary condition for any adaptive learning procedure to be stable. Applying the notion of eductive stability to a simple, cashless forward-looking model, Guesnerie finds that Taylor rules that react too strongly to inflation may not be eductively stable.

Ben McCallum argues that the requirement of stability under least-squares learning is a "compelling <u>necessary</u> condition for a rational expectations (RE) equilibrium to be considered plausible". While previous work by McCallum and others has demonstrated that monetary policy rules that ensure a unique rational expectations equilibrium (i.e., ensure determinacy) are least-squares learnable, this result was based on the assumption that individuals were able to observe the current equilibrium for the economy. More realistically, individuals may only observe lagged data on the economy and, in this case, the close connection between determinacy and learnability no longer holds. In fact, learnability is ensured only under additional, special assumptions. McCallum also explores the requirement that models be "well formulated," where this is interpreted to mean that certain discontinuities in the models' steady state are ruled out. He shows that even when individuals observe current endogenous variables, neither the property of "well-formulated" nor "learnable" implies the other.

Most modern models used for monetary policy analysis assume that nominal prices and wages are sticky, adjusting only slowly over time. In contrast to this approach, Ricardo Ries has, in a series of previous papers, developed the idea that the economy may be characterized not by sticky prices but by sticky information. Agents are inattentive to news because they incur costs of acquiring, absorbing, and processing information. In this volume, Ricardo Reis presents a DSGE model of business cycles and monetary policy, where the only rigidity is pervasive inattention in all markets, and where different agents update their information at different dates. The model is estimated on data for the post-1986 United States and the post-1993 euro area and then applied to conduct several counter-factual policy experiments for both regions. Monetary policy shocks have exhibited little persistence, implying a quick response of most macroeconomic variables to monetary shocks. A pre-announced future policy change increases the response of inflation in comparison to non-announced changes. A gradual policy change has a stronger impact than an expected non-gradual change but only if the gradualist policy is announced and credible. Taylor's (1993) aggressively anti-inflation policy rule would yield higher welfare levels than what is attained by using the actual policy rules estimated for both regions. Finally, compared to flexible inflation targeting under a conventional Taylor rule, welfare would be reduced in both regions if their central banks were to adopt either strict or flexible price-level targeting.

Klaus Schmidt-Hebbel and Carl Walsh apply a parsimonious monetary-policy model to estimate three key unobservable variables – the neutral real rate of interest, the output gap, and the natural rate of unemployment – for three large non-inflation targeting economies (the United States, the euro area, and Japan) and seven inflation-targeting (IT) countries (Australia, Canada, Chile, New Zealand, Norway, Sweden, and the United Kingdom), using quarterly data for 1970-2006 (at most). Country-by-country estimation follows closely the sequential-step procedure developed by Laubach and Williams (2002) for estimating two unobservables for the U.S. The country results reported in this chapter, while mixed, show that trend output growth and the neutral real interest rate vary over time in most countries and the neutral rate of interest is found to vary over time in Chile and the U.S. As discussed above, it is important to consider that key unobservables may vary over time for conducting monetary policy efficiently. Regarding common time trends, Schmidt-Hebbel and Walsh show that the volatilities of inflation, output growth, and the real interest rate have declined in their country sample during the last decades, which is consistent with the great moderation observed world-wide since the early 1990s. The three big economies exhibit neither large nor rising co-movements of key variables over time. However, most smaller IT economies exhibit rising co-movements of key observables and unobservables with the U.S. Finally, on convergence of variable levels observed across countries during the sample period, the authors reject convergence of unobservables in IT countries to the levels estimated for the U.S. and the euro area, but they report convergence of actual growth and interest rates in most IT countries to growth and interest rate levels observed in the U.S. and the euro area.

In their chapter, Martin Melecky, Diego Rodríquez Palenzuela and Ulf Söderström use a model estimated on euro area data to assess the effects of monetary transparency and credibility on inflation and output volatility. The key uncertainty faced by private agents in the model arises from shifts in the central bank's policy rule. These shifts might reflect transitory interest rate movements or they might reflect persistent changes in the central bank's inflation target. The model the authors employ is a forward-looking DSGE model that incorporates, among other aspects, sticky prices and sticky wages. Interestingly, the authors find that the gains from credibly announcing changes in the target inflation rate are relatively small. However, they show that this result depends on the assumption that the private sector fully understands the stochastic process that governs persistence in the target rate. When this aspect of the target rate behavior is not known, the inference problem private agents face is more complicated, and the gains from announcing the target can be much larger, particularly if private agents overestimate the volatility of the target.

Volker Wieland develops a model designed to provide an understanding of the path of gradual disinflation in inflation targeting countries such as Chile. He introduces two new elements into a new Keynesian model to capture disinflationary experiences. First, private firms engage in adaptive learning; in setting prices, they need to forecast future inflation and, to do so, they employ least squares methods to update estimates of a simple forecasting equation. Second, Wieland develops a model of price indexation in which the degree of indexation is endogenously determined. This approach contrasts with the many models that assume some prices are partially indexed to past inflation but which treat the degree of indexation as exogenous. Specifically, whenever a firm has an opportunity to optimally reset its price, it also decides whether to index future price changes to past inflation or to the central bank's inflation target. As a consequence, an immediate disinflation via a reduction in the central bank's inflation target causes firms to quickly drop backward-looking indexation and base indexation on the inflation target. However, the initial impact of this rapid disinflation is a large output decline. The decline in real economic activity can be muted if the central bank carries out a more gradual disinflation. As firms update their assessment of inflation persistence during a gradual disinflation, the real costs of the disinflation decline. However, in the gradual disinflation scenario, firms are less likely to shift their indexation to the central bank's target. Wieland then goes on to analyze the use of temporary inflation targets that gradually decline towards a low steady-state inflation rate. This situation captures the gradual disinflation strategy based on annual inflation targets adopted by Chile during 1990-2000, similar to several other inflation targeting countries that adopted annual inflation targets when actual inflation was still high. Meeting short-term targets helps increase the rate at which firms alter their indexation strategies from being based on lagged inflation to being based on the new inflation targets. This helps in achieving low inflation.

Felipe Morandé and Mauricio Tejada assess the empirical importance of the three classical sources of uncertainty for monetary policy in Chile. Data uncertainty is analyzed by comparing real-time estimates for the output gap among each other and with final-data measures, concluding that the correlations between real-time data and final-data output gap estimates are relatively low. To evaluate the empirical importance of additive uncertainty (associated to the variance of shocks) and multiplicative uncertainty (associate to parameter uncertainty), Morandé and Tejada estimate a small open-economy forward-looking new Keynesian model for Chile, with time-varying parameters and state-dependent variances of disturbances. The results for all model equations show that additive uncertainty dominates multiplicative uncertainty. The estimations support the hypothesis of state-dependent variances linked to two states of either low or high shock volatility. Measures of total uncertainty of both the output gap and inflation have declined over time, and the period of greater stability coincides with full-fledged IT adopted since 2001.

In previous work, Marco del Negro and Frank Schorfheide (and others) have developed the DSGE-VAR model, which relaxes cross-equation restrictions and can be regarded as a structural VAR model but retains many features of the underlying DSGE specification. In this volume, Del Negro and Schorfheide present estimation results for a small open-economy DSGE-VAR model for Chile in 1999-2007. The authors find it helpful to tilt their VAR estimates toward the restriction generated by their DSGE model because the VAR without tight priors is unlikely to provide good forecasts or sharp policy advice. Observed inflation variability was mostly due to domestic shocks. Regarding monetary policy rules, one finding is that the Central Bank of Chile did not respond significantly to exchange-rate and terms-of-trade shocks. Stronger Central Bank response to inflation shocks would have little affected inflation volatility, but a weaker response would have lead to an inflation volatility spike. Del Negro and Schorfheide derive two potentially more general lessons from their exercise. First, the outcomes of policy experiments are very sensitive to the parameters that reflect the law of motion of exogenous shocks. Second, the presence of misspecification – when the DSGE model is rejected relative to a more loosely parameterized model – does not necessarily imply that the answers to the policy exercises obtained from the DSGE model are not robust.

In the final chapter, Manuel Marfán, Juan Pablo Medina, and Claudio Soto specify and estimate a DSGE model for Chile to analyze the macroeconomic effects of several exogenous and policy shocks when private agents suffer from misperceptions about future productivity levels that generate boom-bust cycles, such as those recurrently observed in both emerging-market and industrial economies in the 1990s and the 2000s. The model, based on a three-sector small open-economy forward-looking DSGE specification with several nominal and real rigidities and a Taylor rule, is used to conduct several simulations. The first simulation shows that a boom-bust cycle can be simulated by an unexpected decline and subsequent reversal in the foreign interest rate, which accounts well for the stylized facts observed in Chile during the 1990s. The second simulation focuses on the effects of over-optimistic expectations about future productivity levels and, alternatively, future productivity trends, which ex-post turn out to be wrong. Only over-optimism about productivity trends (not levels) is able to replicate Chile’s cycle, similarly to the foreign-interest rate-induced cycle. Finally, Marfán et al. contrast the macroeconomic effects of alternative monetary policy reactions in response to an increase in trend productivity. If the central bank follows a stricter IT regime, the boom-bust cycle of most macro variables would be amplified. A similar cyclical amplification of the boom-bust cycle is observed when the central bank includes the exchange-rate as an argument in its policy rule, as was actually the case during the partial IT cum exchange-rate band regime adopted until 1999.

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