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Uncertainty and Monetary Policy Experimentation: Empirical Challenges and Insights from Academic Literature

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Abstract

Central banks face considerable uncertainty when conducting monetary policy. Some of the reasons for this include limitations of economic data, the unobservability of key macroeconomic variables such as potential output, structural changes to the economy and disagreements over the correct model for the transmission of monetary policy. At the same time, monetary policy is affected by uncertainty from various sources, including lack of or imperfect observation of economic variables, structural economic changes and possible misspecifications using models. We draw from the academic literature to review some of the key sources of this uncertainty and their implications for the conduct of monetary policy. First, we discuss evidence on release lags and revisions to economic data. We also highlight uncertainty around measuring unobservable variables such as the output gap and the natural rate of unemployment. The strength of a trade-off between these measures of economic slack and inflation—a cornerstone of monetary policy—is itself subject to continuous reassessment. Second, the literature finds that different sources of uncertainty may make the optimal conduct of monetary policy either more or less responsive to economic shocks. Additionally, the benefits of tackling uncertainty by engaging in purposeful monetary policy experimentation are typically small but may become more significant during major structural change or following unprecedented shocks

Topics: Central bank research; Monetary policy and uncertainty; Potential output
JEL codes: E3, E5

Résumé

Les banques centrales font face à une incertitude considérable dans la conduite de la politique monétaire. Cela s'explique notamment par les limites des données économiques, par l'impossibilité d'observer certaines variables macroéconomiques clés comme la production potentielle, par les changements structurels de l'économie et par les désaccords sur le choix du modèle adéquat pour la transmission de la politique monétaire. Parallèlement, la politique monétaire est influencée par divers types d'incertitude, tels le manque ou l'observation imparfaite de variables économiques, les changements économiques structurels et les possibles erreurs de spécification dans l'utilisation des modèles. Nous nous appuyons sur la littérature spécialisée pour examiner quelques-unes des principales sources d'incertitude et leur incidence sur la conduite de la politique monétaire. D'abord, nous analysons les informations disponibles sur les délais de diffusion des données économiques et les révisions qui y sont apportées. Nous nous penchons aussi sur l'incertitude entourant la mesure de variables non observables comme l'écart de production et le taux de chômage naturel. Le degré d'arbitrage entre ces mesures des capacités excédentaires et l'inflation – la pierre angulaire de la politique monétaire – est lui-même réévalué constamment. Ensuite, les études montrent que la conduite optimale de la politique monétaire peut devenir plus ou moins réactive aux chocs économiques selon la source d'incertitude. En outre, chercher à dissiper l'incertitude en procédant à des expérimentations de la politique monétaire donne généralement peu de résultats, mais la démarche peut s'avérer plus utile dans le contexte d'une importante transformation structurelle ou après des chocs sans précédent.

Sujets : Recherches menées par les banques centrales; Incertitude et politique monétaire; Production potentielle
Codes JEL : E3, E5

Introduction

Central banks face considerable uncertainty when conducting monetary policy. Some of the reasons for this include limitations of economic data, the unobservability of key macroeconomic variables such as potential output, structural changes in the economy and disagreements over the correct model of the transmission of monetary policy.

The COVID-19 pandemic brought these issues back to the forefront of policy discussions. Business closures triggered a deep economic downturn that was uncertain both in nature and duration. First, lockdown policies forced entire sectors of the economy shut down, representing an extraordinarily large shock for modern labour markets. Second, the pandemic had an uneven impact across sectors and workers, with some parts of the economy remaining more vulnerable than others. Third, while the pandemic has been an unprecedented shock to the labour market in Canada and elsewhere, labour markets had already been affected by several transformations in recent decades. These transformations include demographic shifts, technological change, globalization and changes in employment relationships due to automation and digitalization. Policy-makers and researchers are still trying to fully understand the dynamics triggered by these transformations. With a major shock such as the COVID-19 crisis exacerbating a labour market that has already undergone significant changes, disentangling trends from cycles has become even more difficult than usual.

The monetary policy response to the COVID-19 crisis was unprecedented in terms of speed, scope and size. Central banks around the world lowered interest rates to their effective lower bound to support economic activity. They also launched a range of liquidity facilities and purchase programs to keep markets functioning. The Bank of Canada committed to holding the policy interest rate at the effective lower bound until economic slack is absorbed. Many decisions need to be made when unwinding the monetary stimulus that was implemented at the onset of the pandemic. These include when to begin unwinding, how quickly to tighten, the order different tools should be adjusted and how to coordinate these adjustments (unwinding asset holdings versus raising policy rates).[1] Central banks will make these decisions in the face of widespread uncertainty about key economic fundamentals such as the maximum sustainable employment and the relationship between inflation and economic slack. Before the pandemic, influential scholars and policy-makers (e.g., Elmendorf 2019 and Evans 2019), had already pointed out that monetary policy may need to feature a higher degree of experimentation, carefully probing the effective boundaries of labour market outcomes.

We review key insights from academic literature about the conduct of monetary policy under uncertainty, addressing the scope for monetary policy experimentation. We start by reviewing some of the key sources of uncertainty central banks face, such as data uncertainty, the measurement of unobservable variables and the trade-off between output and inflation, the Phillips curve. Next, we examine how this affects the conduct of monetary policy. We first discuss the literature that examines the celebrated Brainard (1967) attenuation

[1] The monetary policy response to the COVID-19 crisis was unprecedented in terms of speed, scope and size. Central banks around the world lowered interest rates to their effective lower bound to support economic activity. They also launched a range of liquidity facilities and purchase programs to keep markets functioning. The Bank of Canada committed to holding the policy interest rate at the effective lower bound until economic slack is absorbed.

principle—the idea that monetary policy should respond more cautiously to incoming news when there is uncertainty. Finally, we review the studies that focus on the effects of learning and purposeful monetary policy experimentation.

Our main insights are the following. First, several studies document the uncertainties that central banks face when monitoring the state of the economy and conducting monetary policy. For example, key macroeconomic indicators are announced with long lags (e.g., gross domestic product) and are often revised when more data become available (Faust, Rogers and Wright 2005). The uncertainty is perhaps even greater when it comes to estimating key unobservable variables, such as the output gap (Orphanides and Van Norden 2002) and the natural rate of unemployment (Staiger, Stock and Watson 1997). Furthermore, the Phillips curve—the link between the output or unemployment gaps and inflation—is also subject to much debate about its specification and estimates.[2]

Second, a large body of theoretical work shows that the attenuation principle (Brainard 1967) does not always hold. In various applications, the optimal policy under uncertainty calls for more activism compared with the certainty-equivalent scenario. The main argument brought against monetary policy attenuation hinges on the consideration that "it will pay to make sure current inflation is very stable by reacting more aggressively to shocks" (Walsh 2004). However, the results in the literature are sensitive to the models and the sources of uncertainty considered.

Third, the existing literature finds that learning through experimentation is important for improving the design of monetary policy, but that the gains from purposeful experimentation are typically small (e.g., Cogley et al. 2011). Nevertheless, at times of major structural change or following large shocks, central banks may have little reliable data to inform their policy decisions. In this case, the gains from experimentation could be more significant relative to normal times (e.g., Wieland 2000).

When applied to the economic recovery from the COVID-19 crisis, these results suggest that cautious experimentation could help central banks learn about the maximum level of employment and the relationship between inflation and economic slack. However, cautious experimentation must not weaken the central bank's commitment to achieving its inflation target over the medium term, ensuring that inflation expectations remain anchored (Elmendorf 2019). Clear central bank communication and effective monitoring of labour market conditions with a broad range of indicators and tools are essential ingredients when leveraging the credibility of the inflation target to probe and learn about the maximum level of sustainable employment.

[2] The output and unemployment gaps refer to the differences between actual output and unemployment to their respective potential or natural rates.

Sources of central bank uncertainty

When setting monetary policy, central bankers face large uncertainties about the current state of the economy as well as its state in the future and even in the past. Important unobservable variables such as the output gap and the non-accelerating inflation rate of unemployment (NAIRU) are estimated with large confidence intervals, and their initial real-time estimates are often revised considerably.

Data, revisions and uncertainty about unobservable variables

Macroeconomic data are released with significant lags and are subject to subsequent large revisions. For example, gross domestic product (GDP) in Canada for a given quarter is only released 60 days after the end of that quarter. As Statistics Canada receives more information about the economy, it will often revise this previous release to account for the additional information. A significant amount of literature shows that these revisions are large. The initial estimates of important macroeconomic indicators, such as GDP, are often biased and predictable. For example, Faust, Rogers and Wright (2005) examine GDP announcements in the G7 and find that the large revisions to the initial estimates are often foreseeable. Aruoba (2008) studies the quality of initial releases from many economic indicators in the United States and documents similar results: revisions to initial estimates often do not average out. Tkazc (2010) shows that these results remain true for the release of the national accounts in Canada. However, revisions to Canadian GDP announcements tend to be smaller compared with other member countries of the Organisation for Economic Cooperation and Development (OECD).

Hence, when conducting monetary policy, the uncertainty about the evolution of the macroeconomy does not begin with the forecasts. Even the data used to feed the various macroeconomic models are subject to significant uncertainty and are often revised.

Unobserved variables: uncertainties about the output gap, the natural rate of interest and maximum sustainable employment

Central banks must also estimate important unobservable variables—such as potential output, the level of maximum sustainable employment and the neutral rate of interest—when conducting monetary policy. For example, Champagne, Poulin-Bellisle and Sekkel (2018) show that the Bank of Canada's real-time estimates of the output gap[3] (the difference between actual and potential output) are subject to large revisions, though the revisions were smaller in the past 20 years than they were in the 1990s.[4]

The uncertainty around the estimates of maximum sustainable employment is also well established. For instance, Staiger, Stock and Watson (1997) report that the US NAIRU is imprecisely estimated. They show that it is common for the 95% confidence bands of the NAIRU to be roughly 3 percentage points. Rose (1988) and Setterfield et al. (1992) document similar findings for the Canadian NAIRU. Brouillette et al. (2019)

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[3] Barnett, Kozicki and Petrinec (2009) provide a description of the use of output gaps in the conduct of monetary policy in Canada.

[4] Similar results have been found for other countries. Orphanides and Van Norden (2002) show that real-time econometric estimates of the US output gap based on well-known trend-cycle decompositions are subject to large revisions. Additionally, Orphanides (2003) shows that real-time estimates of the output gap by the staff of the US Federal Reserve Board are also subject to large revisions and uncertainty.

document that the estimated trend of the unemployment rate in Canada continues to feature large confidence intervals.

Finally, a large amount of econometric literature estimates the neutral rate of interest using state-space models and finds very large confidence bands around point estimates (Laubach and Williams 2003). For example, Clark and Kozicki (2005) show that Laubach and Williams' real-time estimates are quite unreliable and subject to significant ex post revisions.

Challenges in identifying trends and cycles in macroeconomic time series are at the heart of the sources of uncertainties discussed above. Difficulties related to filtering techniques and data revisions naturally lead to uncertainty around the estimates of unobservable variables.[5]

From employment and output gaps to inflation: uncertainties about the Phillips curve

The Phillips curve relates inflation to a measure of economic slack, such as the output or the employment gap, and inflation expectations. This relationship represents the central block of modern macroeconomic models used to study the transmission of monetary policy. It also provides central banks with guidance for maintaining output at its potential level, and thereby employment at its maximum level, while keeping inflation sustainably on target. In particular, the slope of the Phillips curve is key to predicting the inflationary pressures that would emerge if the economy were to run above full capacity. Not surprisingly, the Phillips curve has been the object of intense empirical analysis and debates.

A thorough review of the history and empirical evidence on the Phillips curve is beyond the scope of this discussion paper.[6] To help us illustrate our discussions, consider, for example, the structural New Keynesian Phillips curve.

$$\pi_t = \beta E_t \pi_{t+1} + \kappa y_t + u_t \tag{1}$$

relates inflation at time t to expected inflation at time $t+1$, the output gap y_t and a cost-push shock u_t. The parameter β is a time-discount factor and κ is the slope of the Phillips curve. It is important to note that the output gap here, y_t , is measured as the deviation of output and its efficient flexible price level. The reduced-form accelerationist version of the Phillips curve is another specification commonly used in applied work (Stock and Watson 2009):

$$\pi_t - \pi_{t-1} = \theta x_t + \epsilon_t, \tag{2}$$

where changes in the inflation rate relate to the output gap, x_t, measured here as the deviation of output to an empirically estimated measure of economic slack. Another commonly used specification of the Phillips curve uses surveys to proxy for $E_t \pi_{t+1}$, instead of assuming that $E_t \pi_{t+1} = \pi_{t-1}$, as in the accelerationist version of the Phillips curve (Ball and Mazumder 2019).

As stated above, the general idea behind Phillips curves is that, as the economy grows and the unemployment rate falls, workers demand progressively higher wages, production costs rise, and firms

[5] For example, some of the challenges associated with trend-cycle decompositions include the choice of the appropriate technique and end-of-sample issues. For a recent discussion of these problems, see Hamilton (2018).

[6] For a more in-depth review of the evolution and empirical evidence on the US Phillips curve, see Gordon (2011).

consequently charge higher prices for their products. Hence, one expects a positive relationship between inflation and the output gap.

Aside the apparent simplicity of the equations above, various issues emerge that make it particularly challenging to estimate them, as extensively discussed by Mavroeidis, Plagborg-Møller and Stock (2014) and more recently by Hazell et al. (2020), among many others.

First, the measure of slack, or the output gap, may covary with other variables, such as inflation expectations. While researchers try to control for variables that proxy for inflation expectations, research by Mavroeidis, Plagborg-Møller and Stock (2014) shows that small changes to the set of variables used to proxy for inflation expectations can lead to widely different estimates of the slope of the Phillips curve. They conclude that there is simply not enough information in aggregate macroeconomic data in Phillips curve regressions to separately identify the slope and inflation expectations coefficients.

Second, the successful conduct of monetary policy might make it harder to identify the slope of the Phillips curve. This is because aggregate supply shocks, such as an oil shock or a productivity shock, induce a negative correlation in output gap and inflation, whereas demand shocks generate a positive comovement between economic activity and inflation. If the aggregate data used to estimate the Phillips curve is contaminated with supply shocks, coefficients will be biased toward zero. The more effectively central banks offset demand shocks, the harder it becomes to identify the Phillips curve. McLeay and Tenreyro (2020) have (also) formally shown/demonstrated this (point).

Estimates of the Phillips curve are therefore often sensitive to the sample size and specification details. Recently, a growing literature is exploring cross-sectional information to better identify the slope of the Phillips curve.[7] By exploring demand-driven local output fluctuations, researchers aim to better identify the slope of the Phillips curve because central banks should not respond to localized demand shocks.

Notwithstanding these difficulties in estimating Phillips curves, there is a consensus that the slope of Phillips curves has flattened since the late 1980s or early 1990s; however, the literature still debates the extent of the flattening (see Hazell et al. 2020 and Del Negro et al. 2020). Nonetheless, researchers generally agree that the slope of the Phillips curve has been quite flat since the 1990s. This means that recent large fluctuations in the output gap are consistent with relatively stable inflation. The Canadian evidence is broadly in line with the US evidence. Beaudry and Doyle (2000) estimate an accelerationist version of the Phillips curve for Canada and detect a decrease of the slope around 1990. Kichian (2001) finds similar results by estimating a Phillips curve with time-varying parameters. Landry and Sekkel (2022) revisit this question using vector autoregressive models and find evidence of a flattening of the Phillips curve in Canada after the 1990s. Estimates using the latest vintage of the Bank of Canada's Terms-of-Trade Economic Model, ToTEM III, also imply a relatively flat Phillips curve.

[7] See, among others, Fitzgerald et al. (2020); Hooper, Mishkin and Sufi (2020); McLeay and Tenreyro (2020) and Hazell et al. (2020).

Recent evidence examines the causes of the decline in the slope of the Phillips curve. The literature points to forces that reduce the sensitivity of the prices of goods to cost pressures, such as globalization and the increased importance of global supply chains (Forbes 2019a, 2019b), higher import competition from low wage countries (Auer and Fischer 2010) and changes in the production network of the economy (Rubbo 2020).

A new empirical approach uses regional data to identify the slope of the Phillips curve. Hazell et al. (2020) find that the slope of the Phillips curve has been flat since the 1980s. Furthermore, they argue that the sharp drop of inflation in the United States during the 1980s was mainly due to shifting long-term inflation expectations. Similarly, Fitzgerald et al. (2020) use data from US metropolitan statistical areas from 1976 to 2010 and find a stable relationship between the unemployment rate and inflation. Babb and Detmeister (2017); Hooper, Mishkin and Sufi (2020); and McLeay and Tenreyro (2020) also argue in favour of using disaggregated regional data to better estimate the Phillips curve. To date, no similar systematic analysis using regional data to estimate the Canadian Phillips curve has been conducted.

While most of the literature focuses on estimating the magnitude of the slope of the Phillips curve, a subset of studies investigates the presence of nonlinearities. For instance, with a convex Phillips curve, the curve's slope increases when the economy grows above potential, implying a higher inflation risk near the maximum level of sustainable employment. While evidence of a convex wage Phillips curve is robust, the evidence supporting a convex Phillips curve for prices is mixed. Some studies, such as Babb and Detmeister (2017), find evidence of a small convexity the using US data. However, they also argue that linear and nonlinear Phillips curves produce very similar inflation forecasts. Other studies, such as Eliasson (2001), do not find evidence of nonlinearities. Moretti, Onorante and Zakipour (2019) reach the same conclusion using data for the euro area. Laxton, Rose and Tambakis (1999) argue that the adopted measure of economic slack greatly influences inference about asymmetries in the Phillips curve.

Examining recent data for Canada with a non-parametric model, Brouillette et al. (2018) find no evidence of convexity in the Canadian Phillips curve. As discussed above, identifying the parameters of the Phillips curve is challenging. It is therefore not surprising that the literature has yet to converge on the empirical relevance of nonlinearities in the slope parameter.

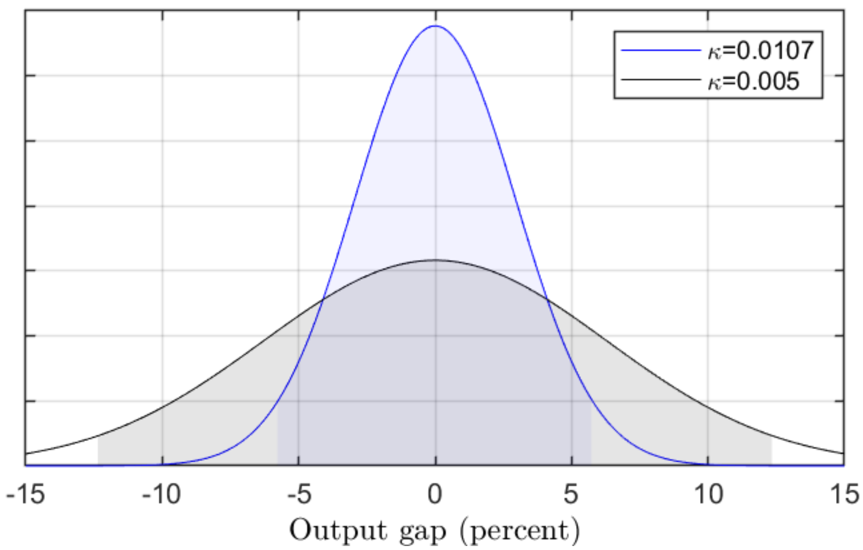
Can we learn about the output gap through inflation outcomes and the Phillips curve?

To conclude this section, we link our discussion of the Phillips curve to the uncertainties around the estimate of the output gap. More precisely, we ask the following question: what can we say about the current state of the output gap given an observed rate of inflation and estimates of the Phillips curve? In other words, if we knew the parameters of the Phillips curve and the volatility of the cost-put shocks (u_t) in equation (1), could we use it to construct a distribution for the output gap? And moreover, what impact does a flattening of the Phillips curve have on the distribution of output gaps? To answer these questions, we solve equation (1) forward and invert it to express the output gap as a function of inflation and the cost-push shocks.[8]

[8] See the Appendix for a more in-depth discussion of the underlying framework and its calibration that generate Figure 1.

The shaded areas of **Figure 1** highlight where output gap would be with 95% confidence for two different estimates of the slope of the Phillips curve, under the assumption that inflation is at its 2% target. We consider estimates of the slope for before and after the 1990s, 0.0107 and 0.005 respectively, from Hazell et al. (2020). The blue line depicts the distribution with the steeper Phillips curve (0.0107), whereas the black line shows the one with the flatter Phillips curve (0.005). The distribution of the output gap becomes more dispersed as the slope of the Phillips curve flattens. As a result, statistical inference on the output gap becomes harder with a flatter Phillips curve. As discussed previously, a flatter Phillips curve implies that a greater range of output gaps is consistent with a relatively stable inflation.

Figure 1: Distribution of the output gap for 2% inflation



Uncertainty and monetary policy experimentation

We now turn to the implications of these sources of uncertainty for the conduct of monetary policy. This section presents insights from the literature, addressing the costs and benefits of purposeful monetary policy experimentation at times of heightened uncertainty.

The canonical framework of monetary policy analysis assumes that the central bank sets the nominal interest rate to minimize a quadratic loss function. A set of linear equations describes the economy. In most models, uncertainty is incorporated as additive shocks to these linear equilibrium conditions, capturing factors outside the model that lead to variation in economic activity. In this case, the optimal policy responds to the mean of the distribution of shocks. According to the so-called certainty equivalence principle, any information on higher moments is irrelevant.

Starting with Brainard (1967), extensive literature addresses how uncertainty affects the conduct of monetary policy when the certainty equivalence no longer holds. Brainard's celebrated result is the so-called attenuation (or conservatism) principle: in the presence of (parameter) uncertainty, monetary policy should respond more cautiously to incoming news.

Several studies reassessed and challenged Brainard's (1967) result. A strand of the literature focuses on the implications of uncertainty without addressing the benefits and costs of purposeful monetary policy experimentation. A subset of studies incorporates central banking learning and experimentation in the analysis. We now review the main insights from this research.

Monetary policy attenuation and activism without learning

A rich literature studies how to deal with irreducible uncertainty in the conduct of monetary policy without addressing the implications of central bank learning and experimentation. The focus is on parameter and model uncertainty, data, measurement uncertainty as well as on the consequences of nonlinearities in the Phillips curve. The central insight from this literature is that the attenuation principle does not always hold. The main argument brought against the attenuation principle hinges on the consideration that "it will pay to make sure current inflation is very stable by reacting more aggressively to shocks" (Walsh 2004). In various applications, the optimal policy under uncertainty calls for more activism compared with the certainty-equivalent scenario. However, the results are generally sensitive to the specific models and the sources of uncertainty considered.

A first strand of the literature studies the consequences of model and parameter uncertainty using Bayesian optimal control methods, i.e., assuming the central bank has prior probabilities over a set of unknown parameters or models. Uncertainty provides an incentive to implement gradual interest rate movements to limit policy mistakes stemming from incorrect parameter estimates (e.g., Sack 1998 and Williams 2013). However, Brainard's attenuation principle does not always hold. For instance, Söderström (2002) shows that aggressive policy can be necessary when uncertainty bears on the persistence of inflation in a model with adaptive expectations. Kimura and Kurozumi (2007) reach a similar conclusion about uncertainty on the fraction of firms that form expectations in a rule-of-thumb, adaptive fashion. Uncertainty about the slope of the Phillips curve can also imply that optimal monetary policy is more aggressive compared with the full information scenario, depending on the degree of persistence of cost-push shocks (Ferrero, Pietrunti and Tiseno 2019). Finally, concerns over uncertainty can create a cautiousness bias, shifting inflation expectations away from the target (Dupraz, Guilloux-Nefussi and Penalver 2020).

A second strand of the literature uses robust-control methods (Hansen and Sargent 2007) to study uncertainty about events with unknown or unmeasurable probabilities (Knightian uncertainty). Concerns about worst-case scenarios can also lead to amplification rather than attenuation in the optimal monetary policy response (e.g., Giannoni 2002; Onatski and Stock 2002; Tetlow and Von zur Muehlen 2001). However, Barlevy (2011) argues that aggressiveness is not an inherent feature of robustness but is specific to the models studied in the literature. In some environments, the robust policy exhibits an even more extreme form of the same attenuation principle that Brainard demonstrated, for essentially the same reason: the asymmetry between how passive and active policies leave the policy-maker exposed to risk tends to favour passive policies.[9]

[9] A related line of work studies the robustness of simple monetary policy rules in the presence of model or parameter uncertainty. This literature aims to compare the performance of alternative rules across a range of possible models and parameter values assuming the central bank has flat priors (e.g., Levin, Wieland and Williams, 1999 and 2003). While this literature looks for policy rules that work well across various models, it does not try to find the optimal robust rule.

With respect to measurement uncertainty, the literature studies optimal monetary policy when the central bank relies on noisy real-time data and on imprecise estimates of economic fundamentals. Influential studies argue that the central bank should respond more cautiously to variables measured with an error such as the output gap or the unemployment gap (e.g., Sack and Wieland 2000; Orphanides 2003; Orphanides and Williams 2007; Cateau 2007). However, other authors have counselled against such an approach (e.g., Svensson 1997, 2017; Blanchard, Dell'Ariccia and Mauro 2010). According to this view, the complexity of monetary policy makes it desirable to respond to resource slack, despite acknowledged shortcomings in its measurement.[10]

Finally, a strand of the literature discusses the implications of uncertainty in the presence of nonlinearities in the Phillips curve or at the effective lower bound (ELB). Nonlinearities in the trade-off between inflation and output can lead to a more cautious or aggressive response when the central bank faces heightened uncertainty. For instance, a kink in the New Keynesian Phillips curve (e.g., a flat Phillips curve for a range of output-gap values and a positively sloped curve outside the range) can lead to an inaction zone that increases with the central bank's uncertainty. In this case, uncertainty creates an option value of waiting (e.g., Orphanides and Wieland 2000). At the same time, with a convex Phillips curve, the optimal monetary policy can become more active when uncertainty about the impact of policy increases (Shaling 2004). Finally, the ELB on nominal interest rates can motivate the central bank to adopt a looser policy when it faces uncertainty about expected inflation and the output gap—the risk-management channel Evans et al. (2015) emphasize.

Learning and experimentation

A second strand of the literature addresses the implications of central bank learning, discussing whether it can be optimal for central banks to experiment purposefully to reduce uncertainty (active learning henceforth).

Prominent macroeconomists such as Blinder and Lucas have forcefully recommended against purposefully experimenting on real economies to refine the policy-maker's knowledge. Blinder (1998, p. 11) states, "while there are some fairly sophisticated techniques for dealing with parameter uncertainty in optimal control models with learning, those methods have not attracted the attention of either macroeconomists or policymakers. There is a good reason for this inattention, I think: You don't conduct policy experiments on a real economy solely to sharpen your econometric estimates." Lucas (1981, p. 288) remarks, "Social experiments on the grand scale may be instructive and admirable, but they are best admired at a distance. The idea, if the marginal social product of economics is positive, must be to gain some confidence that the component parts of the program are in some sense reliable prior to running it at the expense of our neighbors." An aversion to experimentation also runs through Friedman's advocacy of a *k*-percent money growth rule.

Various studies assess the merit of these views.[11] The predominant approach considers a Bayesian decision problem under model or parameter uncertainty. Intuitively, a Bayesian policy-maker has an incentive to vary the policy instrument to generate additional information. As the central bank's posterior distribution about

[10] Often, the difference in recommendations boils down to whether the estimation and control stages of the central bank problem are treated separately. When this is the case, certainty equivalence can be preserved, provided that measurement is the only source of uncertainty. Otherwise, the response to the noisy indicator is attenuated.

[11] A related but different literature addresses how the central bank's learning has affected US inflation dynamics (e.g., Cogley and Sargent 2005; Primiceri 2005).

parameters and model probabilities becomes endogenous, the central bank must simultaneously control the policy target and estimate (learn) the impact of its policy actions.[12] A trade-off between estimation and control arises because policy actions influence learning and provide information to improve economic stabilization.

Earlier studies focus on Bayesian optimal policy and experimentation in models without forward-looking variables. In this context, all dynamics are due to central bank learning. Only a few more recent studies extended the analysis to models with forward-looking endogenous variables, a key component of modern policy-relevant models.

A common result across studies is that the optimal policy typically includes an experimentation component—deliberate policy actions designed to help the central bank better understand the economy's behaviour (Schmidt-Hebbel and Walsh 2009). Optimal experimentation can also lead to a more aggressive monetary policy response because an activist policy can generate information that may improve future macroeconomic stabilization (e.g., Wieland 2006; Tesfaselassie, Schaling and Eijffinger 2011).

However, experimental motives are typically weak, and the benefits from active learning are quantitatively small (Cogley et al. 2011). Cogley, Colacito and Sargent (2007) show that a passive learner (i.e., a central bank that learns but does not design policy to experiment) induces enough variation in the data to learn as quickly as a central bank that actively experiments. In their model, this occurs because aggregate shocks are large enough to provide ample unintentional experimentation. Svensson and Williams (2008) study the problem of a policy-maker who seeks to set optimal policy in an economy where the true economic structure is unobserved. They find that passive learning ("adaptive optimal policies" in the authors' language) approximates well the full Bayesian optimal policy with experimentation.

Experimentation only has noticeable benefits for extreme levels of uncertainty. Thus, while learning is important for improving policy design in the face of uncertainty, the gains from experimentation are small. When robust control is considered, concerns about possible misspecification of the decision problem further temper the degree of experimentation (Cogley et al. 2008). Earlier contributions share similar findings. For instance, Wieland (2006) studies optimal monetary policy in the presence of uncertainty about the natural rate of unemployment, the trade-off between inflation and unemployment in the short run and the degree of inflation persistence. His reduced-form model incorporates rational learning by both the central bank and market participants. On the one hand, uncertainty motivates the policy-makers to move more cautiously than if they knew the true parameters. On the other hand, uncertainty motivates policy-makers to learn through an element of policy experimentation.

While the optimal policy balances the cautionary and activist motives, the optimal response to inflation remains less aggressive than a policy that disregards parameter uncertainty (unless uncertainty is high and inflation is close to the target). In a similar model, Yetman (2000) studies whether a central bank that has increased its credibility should follow a more aggressive policy to obtain more precise estimates of potential output. For

[12] An earlier, computationally oriented literature focused on the performance of alternative decision rules in multi-period control problems. This research compared certainty-equivalent and cautionary decision-making with active experimentation. In parallel, a second strand of the literature studied the possibility of incomplete learning and the conditions under which complete learning would occur in the long run.

plausible parameter values, the optimal amount of probing is small and varies little with credibility. Isard et al. (2001) consider a model in which experimentation only occurs when inflation is low in an attempt by the monetary authority to better identify the (unknown, time-varying) NAIRU. They also incorporate endogenous credibility, showing that experimentation may result in a slightly lower average unemployment rate, but it does so at the expense of a rise in average inflation rates. Finally, Ellison and Valla (2001) discuss the implications of experimenting with monetary policy for inflation expectations. They show that an activist policy designed to learn and reduce future uncertainty can increase volatility in inflation expectations, with detrimental outcomes for welfare. In addition, frequent reversals to the interest rate (interest rate movements in the opposite direction to recent changes) can generate learning costs for the central bank and the private sector (Ellison 2006).

Searching for the maximum sustainable employment

While the previous literature finds small gains from purposeful monetary policy experimentation, the benefits and risks of active learning may depend on the prevailing macroeconomic outlook. For instance, central banks may have little reliable data to inform their policy decision during periods of major structural change or following large aggregate shocks. In these situations, the gains from purposeful experimentation could be more significant than they are in normal times. Wieland (2000) makes this point by studying the reunification of Germany in 1990, when the Bundesbank faced substantial uncertainty about the implementation and effects of monetary policy as a result of monetary union. The uncertainty extended far beyond determining how to appropriately adjust the size of the money stock, including uncertainty about the money multiplier and money demand, given the little information available about the portfolio choices of East Germans. Studying this historical episode, Wieland argues that the gains from active learning could be substantial.

The benefits and risks of active learning also apply to the macroeconomic outlook following the COVID-19 pandemic. Coupled with the profound structural change that took place in the labour market over the past few decades, the unprecedented shock induced by the pandemic poses new challenges for the conduct of monetary policy.[13] The nature of the recession and the pre-existing labour market trends have made it more difficult for central banks to determine the level of maximum sustainable employment. Widespread uncertainty could result in larger incentives to experiment, maintaining an accommodative monetary stance to learn about the boundaries of the attainable labour market outcomes. Such an approach would also be consistent with Brainard's conservativism, ensuring a prudent reversal of accommodative monetary policy in the face of high uncertainty.

The risks and potential costs of purposeful experimentation may be also lower relative to the past. Well-anchored inflation expectations imply that anticipated inflation is less sensitive to actual inflation. Thus, even if unusually strong growth and low unemployment could push inflation above target, the rise in expected inflation would not persist. Moreover, a relatively flat Phillips curve would provide additional leeway for central banks to exert patience in raising interest rates when the unemployment rate reaches its estimated natural level.

However, it is important to note that a flatter Phillips curve also implies that reversing an increase in inflation expectations would be more costly in terms of lost output. Thus, when inflation is relatively insensitive to

[13] Structural forces include demographic changes, technological change, globalization and shifts in employment relationships due to automation and the emergence of the gig economy.

unemployment, it is paramount that inflation expectations remain anchored because an inflationary spiral would result in high unemployment for a lengthy period (Elmendorf 2019). Monetary policy experimentation must not weaken the central bank's commitment to achieving its inflation target over the medium term, ensuring that inflation expectations remain anchored.[14] Clear central bank communication and an effective monitoring of labour market conditions are essential elements when leveraging the credibility of the inflation target to probe the maximum level of sustainable employment.

We note that the gains from probing a hot economy could extend beyond central bank learning. To the extent that the pandemic has left workers discouraged and detached from the labour force, plentiful job opportunities could draw them back in, increasing labour force participation. Moreover, a hot economy could contribute to avoiding hysteresis, i.e., the possibility that periods of weak demand result in higher structural unemployment, preventing economic activity from returning to the pre-recession trend (Yellen 2017). See Garga and Singh (2020), Acharya et al. (2020) and Vinci and Licandro (2020) for a discussion of these issues.[15]

Conclusions

We reviewed the literature about the effects of uncertainty on the conduct of monetary policy.

We first discussed empirical work that documents the sources of uncertainty faced by central banks when monitoring the state of the economy. Key macroeconomic indicators are announced with a lag and are often revised once more data become available. Estimating key unobservable variables such as the maximum level of sustainable employment and the slope of the Phillips curve also features significant empirical challenges that result in additional uncertainty.

We then turned to literature that addresses the implications of uncertainty for the conduct of monetary policy. Various studies support Brainard's (1967) well-known attenuation principle—the idea that it is optimal for monetary policy to react more cautiously to incoming news and shocks in the presence of uncertainty. However, other studies reach an opposite conclusion, calling instead for monetary policy activism. In general, the results are sensitive to the models and the sources of uncertainty considered.

The literature also shows that central bank learning improves the design of monetary policy, while the gains from purposeful policy experimentation are typically small. Nevertheless, at times of structural change or following large shocks—i.e., when the macroeconomic outlook is more uncertain—the central bank may have little reliable data to inform its policy decisions. In this case, the gains from experimentation can be significant relative to normal times.

[14] Balancing risks also requires considering risks to financial stability. These include asset prices vulnerabilities (e.g., prices rising above a value that fundamentals can justify), balance sheet vulnerabilities (e.g., a growing mismatch between assets and liabilities) and vulnerabilities in the allocation of risk (e.g., when the holders of the riskier assets are not able to manage and absorb risk).

[15] Garga and Singh (2021) argue that ex ante commitment to running a high-pressure economy can eliminate hysteresis when monetary policy is constrained by the ELB. Acharya et al. (2020) show that monetary policy must act aggressively following a large shock to prevent a slow recovery or, even worse, a permanent unemployment trap. Vinci and Licandro (2020) argue that in a deep and persistent recession where the ELB binds, revisions of potential output measures may weaken the impact of monetary policy. In this case, the economy recovers to a lower trend.

These findings have implications for the conduct of monetary policy in the post-pandemic macroeconomic outlook. With heightened uncertainty, cautious experimentation could help central banks learn about the maximum level of sustainable employment and the relationship between inflation and economic slack. Effective communication and the monitoring of labour market conditions with a broad range of indicators and tools are key elements when leveraging the credibility of the inflation target to probe and learn about the maximum level of sustainable employment.

Appendix: How informative is inflation for the state of the business cycle?

This Appendix presents the underlying analysis for the discussion about inferring the level of potential output with the slope of the Phillips curve. We develop a formal model and then perform its quantitative assessment after calibrating it.

The economy. We consider a model economy with inflation (deviations from target) π_t evolving according to a New Keynesian Phillips curve (NKPC):

$$\pi_t = \beta E_t \pi_{t+1} + \kappa y_t + u_t,$$

where u_t are the identically and independently distributed cost-push shocks, y_t is the output gap that follows an autoregressive process of order one, β is the time-discount factor, and κ is the slope of the Phillips curve. Solving the equation above forward, we obtain:

$$\pi_t = \frac{\kappa}{1-\beta\rho} y_t + u_t,$$

where ρ is the autoregressive coefficient of the output gap. Further inverting this relation:

$$y_t = \frac{1-\beta\rho}{\kappa}(\pi_t - u_t).$$

The NKPC and its implications described above are assumed to be known by the central bank.

Output gap inference. However, the central bank does not observe either the output gap y_t or the realizations of u_t. Let F denote the cumulative distribution function of the cost-push shocks. We assume that F is known, thus the distribution of the output gap conditional on (observable) inflation is also known. Let $y^* > 0$ be the maximum mistake that one is willing to accept when closing the output gap. We can then characterize the probability of output gap staying within the desired bounds as follows:

$$\begin{aligned} Prob(-y^* \leq y_t \leq y^* \mid \pi_t) &= Prob(y_t \geq -y^* \mid \pi_{t_t}) - Prob(y_t \geq y^* \mid \pi_t) \\ &= F\left(\pi_t + \frac{\kappa}{1-\beta\rho} y^*\right) - F\left(\pi_t - \frac{\kappa}{1-\beta\rho} y^*\right), \end{aligned}$$

which is monotonically increasing in κ:

$$\frac{\mathrm{dProb}(-y^* \leq y_t \leq y^* \mid \pi_t)}{d\kappa} = \frac{y^*}{1-\beta\rho}\left[f\left(\pi_t + \frac{\kappa}{1-\beta\rho} y^*\right) + \mathrm{f}\left(\pi_t - \frac{\kappa}{1-\beta\rho} y^*\right)\right] > 0.$$

This characterization shows that the output gap also becomes more sensitive to changes in inflation when the Phillips curve flattens so that, for a given volatility of the cost-push shocks, the probability of output gap staying within the desired bounds decreases.

Calibration. The main parameter to calibrate is the slope of the Phillips curve, κ. We take two values from Hazell et al. (2020). First, the pre-1990s value of the slope is 0.0107. Second, the post-1990s value of the slope is 0.005. Next, we estimate the autoregressive coefficient of this process, ρ, using quarterly Canadian output gap time series from 1992 to 2019. We obtain an estimate of 0.915. Additionally, we use the time discount factor, β, equal to 0.995.

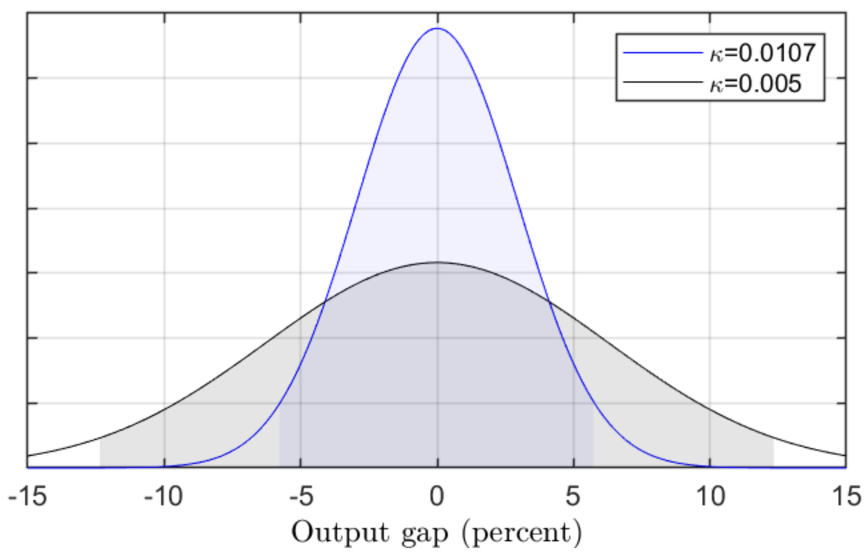
Given these parameter values, we determine the volatility of the cost-push shocks using second moments of the time series for the output gap and year-over-year core inflation, using data from 1992 to 2019 for both. We compute the variances of these two variables and combine them using the following formula to calculate the variance of the cost-push shocks:

$$Var(u_t) = Var(\pi_t) - \left(\frac{\kappa}{1-\beta\rho}\right)^2 Var(y_t),$$

where we use the post-1990s value of the slope of the Phillips curve.

Given the calibration above, **Figure 1**, also displayed in the main text, shows the model-implied density of the output gap conditional on inflation being on target ($\pi_t = 0$) together with 95% confidence intervals (denoted with a shaded area).

Figure 1 shows quantitatively how the distribution of the output gap conditional on inflation becomes, all else equal, more dispersed as the NKPC flattens. Thus, a flattening of the Phillips curve makes any statistical inference on the output gap on the basis of inflation less reliable .



References

Acharya, S., J. Bengui, K. Dogra and S. L. Wee. 2020. "Escaping Unemployment Traps." *mimeo*.

Aruoba, S. B. 2008. "Data Revisions Are Not Well Behaved." *Journal of Money, Credit and Banking 40 (*2/3): 319–340.

Auer, R. .and A. M. Fischer., 2010.. "The Effect of Low-Wage Import Competition on US Inflationary Pressure." *Journal of Monetary Economics 57* (4): 491–503.

Babb, N. R. and A. K. Detmeister. 2017. "Nonlinearities in the Phillips Curve for the United States: Evidence Using Metropolitan Data." Finance and Economics Discussion Series Paper No. 2017-070.

Ball, L. and S. Mazumder. 2019. "A Phillips Curve with Anchored Expectations and Short-Term Unemployment." *Journal of Money, Credit and Banking* 51 (1): 111–137.

Barlevy, G. 2011. "Robustness and Macroeconomic Policy." *Annual Review of Economics* 3: 1–24.

Barnett, R., S. Kozicki and C. Petrinec. 2009. "Parsing Shocks: Real-Time Revisions to Gap and Growth Projections for Canada." *Federal Reserve Bank of St. Louis Review* 91 (4): 247–266.

Beaudry, P. and M. Doyle. 2000. "What Happened to the Phillips Curve in the 1990s in Canada?" In *Proceedings of a seminar held by the Bank of Canada*.

Blanchard, O., G. Dell'Ariccia and P. Mauro. 2010. "Rethinking Macroeconomic Policy." *Journal of Money, Credit and Banking* 42 (s1): 199–215.

Brainard, W. C. 1967. "Uncertainty and the Effectiveness of Monetary Policy." *American Economic Review* 57 (2): 411–425.

Brouillette, D., M. Dockrill, H. Lao and L. Savoie-Chabot. 2018. "Bending the Curves: Wages and Inflation." Bank of Canada Staff Analytical Note No. 2018-15.

Brouillette, D., M. N. Robitaille, L. Savoie-Chabot, P. St-Amant, B. Gueye and E. Nelson. 2019. "The Trend Unemployment Rate in Canada: Searching for the Unobservable." Bank of Canada Staff Working Paper No. 2019-13.

Cateau, G. 2007. "Monetary Policy Under Model and Data-Parameter Uncertainty." *Journal of Monetary Economics* 54: 2,083–2,101.

Champagne, J., G. Poulin-Bellisle and R., Sekkel. 2018. "The Real-Time Properties of the Bank of Canada's Staff Output Gap Estimates." *Journal of Money, Credit and Banking 50* (6): 1,167–1,188.

Clark, T. E. and S. Kozicki. 2005. "Estimating Equilibrium Real Interest Rates in Real Time." *North American Journal of Economics and Finance 16* (3): 395–413.

Cogley, T., R. Colacito, L. P. Hansen and T. J. Sargent. 2008. "Robustness and Monetary Policy Experimentation." *Journal of Money, Credit and Banking* 40 (8): 1,599–1,623.

Cogley, T., R. Colacito and T. J.Sargent. 2007. "Benefits from US monetary policy experimentation in the days of Samuelson and Solow and Lucas." *Journal of Money, Credit and Banking* 39 (s1): 67–99.

Cogley, T., B. De Paoli, C. Matthes, K Nikolov and T. Yates. 2011. "A Bayesian approach to optimal monetary policy with parameter and model uncertainty." *Journal of Economic Dynamics and Control* 35 (12): 2,186–2,212.

Cogley, T. and T. J. Sargent. 2005. "The conquest of US inflation: Learning and robustness to model uncertainty." *Review of Economic Dynamics* 8 (2): 262–302.

Del Negro, M., M. Lenza, G. E. Primiceriand and A. Tambalotti. 2020. "What's Up with the Phillips Curve?" *Brookings Papers on Economic Activity*: 301–357.

Dupraz, S., S. Guilloux-Nefussi and A. Penalver. 2020. "A Pitfall of Cautiousness in Monetary Policy." Banque de France Working Paper No. 758.

Eliasson, A.-C. 2001. "Is the Short-Run Phillips Curve Nonlinear? Empirical Evidence for Australia, Sweden and the United States." Sveriges Riksbank Working Paper Series No. 124.

Ellison, M. 2006. "The learning cost of interest rate reversals." *Journal of Monetary Economics* 53 (8): 1,895–1,907.

Ellison, M. and N. Valla. 2001. "Learning, uncertainty and central bank activism in an economy with strategic interactions." *Journal of Monetary Economics* 48 (1): 153–171.

Elmendorf, D. W. 2019. "Getting and Keeping a High-Pressure Economy," Speech to Fed Listens: A Hot Economy: Sustainability and Trade-offs, Federal Reserve Bank of San Francisco (September 26).

Evans, C. 2019. "Welcome and Introduction," Speech to Fed Listens: Monetary Policy's Impact on Workers and Their Communities in Chicago, Illinois, Federal Reserve Bank of Chicago (October 17).

Faust, J., J. H. Rogers and J. H. Wright. 2005. "News and Noise in G-7 GDP Announcements." *Journal of Money, Credit and Banking* 37 (3): 403–419.

Ferrero, G., M. Pietrunti and A. Tiseno. 2019. "Benefits of Gradualism or Costs of Inaction? Monetary Policy in Times of Uncertainty." Bank of Italy Temi di discussione (Economic Working Papers) No. 1205.

Fitzgerald, T. J., C. J. Jones, M. Kulish and J. P. Nicolini. 2020. "Is There a Stable Relationship Between Unemployment and Future Inflation?" Federal Reserve Bank of Minneapolis Staff Report No. 614.

Forbes, Kristin J. 2019a. "Inflation Dynamics: Dead, Dormant, or Determined Abroad?" *Brookings Papers on Economic Activity*, Fall, 257–338.

Forbes, K. J. 2019b. "How Have Shanghai, Saudi Arabia, and Supply Chains Affected US Inflation Dynamics?" *Federal Reserve Bank of St. Louis Review*, 101(1), 27–44.

Garga, V. and S. R. Singh. 2021. "Output Hysteresis and Optimal Monetary Policy." *Journal of Monetary Economics* 117: 871–886.

Giannoni, M. P. 2002. “Does Model Uncertainty Justify Caution? Robust Optimal Monetary Policy in a Forward-Looking Model.” *Macroeconomic Dynamics* 6 (1): 111–144.

Gordon, R. J. 2011. “The History of the Phillips Curve: Consensus and Bifurcation.” *Economica 78* (309): 10–50.

Hamilton, J. D. 2018. “Why You Should Never Use the Hodrick-Prescott Filter.” *Review of Economics and Statistics* 100 (5): 831–843.

Hansen, L. P. and T. J. Sargent. 2007. *Robustness*. Princeton University Press.

Hazell, J., J. Herreño, E. Nakamura and J. Steinsson. 2020. “The Slope of the Phillips Curve: Evidence from US States.” *National Bureau of Economic Research* Working Paper No. 28005.

Hooper, P., F. S. Mishkin and A. Sufi. 2020. “Prospects for Inflation in a High Pressure Economy: Is the Phillips Curve Dead or Is it Just Hibernating?” *Research in Economics 74* (1): 26–62.

Isard, P., D. Laxton and A.-C. Eliasson. 2001. “Inflation Targeting with NAIRU Uncertainty and Endogenous Policy Credibility.” *Journal of Economic Dynamics and Control* 25 (1–2): 115–148.

Kichian, M. 2001. “On the Nature and the Stability of the Canadian Phillips Curve.” Bank of Canada Staff Working Paper No. 2001-4.

Kimura, T. and T. Kurozumi. 2007. “Optimal Monetary Policy in a Micro-Founded Model with Parameter Uncertainty.” *Journal of Economic Dynamics and Control* 31 (2): 399–431.

Laubach, T. and J. C. Williams. 2003. “Measuring the Natural Rate of Interest.” *Review of Economics and Statistics 85* (4): 1,063–1,070.

Landry, A. and R. Sekkel. *forthcoming*. “Has the Canadian Phillips Curve Flattened? Evidence from VARs.” Bank of Canada Staff Analytical Note.

Laxton, D., D. Rose and D. Tambakis. 199). “The US Phillips Curve: The Case for Asymmetry”. *Journal of Economic dynamics and Control*, 23(9–10), 1,459–1,485.

Levin, A. T., V. Wieland and J. C. Williams. 1999. “Robustness of Simple Monetary Policy Rules Under Model Uncertainty.” National Bureau of Economic Research *Monetary Policy Rules*: 263–318.

Levin, A. T., V. Wieland and J. C. Williams. 2003. “The Performance of Forecast-Based Monetary Policy Rules Under Model Uncertainty.” *American Economic Review* 93 (3): 622–645.

Mavroeidis, S., M. Plagborg-Møller and J. H. Stock. 2014. “Empirical Evidence on Inflation Expectations in the New Keynesian Phillips Curve.” *Journal of Economic Literature* 52 (1): 124–188.

McLeay, M. and S. Tenreyro. 2020. “Optimal Inflation and the Identification of the Phillips Curve.” *NBER Macroeconomics Annual 2019* 34 (1): 199–255.

Moretti, L., L. Onorante and S. Zakipour-Saber, S. 2019. “Phillips Curves in the Euro Area.” *ECB Working Paper* No. 2295

Onatski, A. and J. H. Stock. 2002. "Robust Monetary Policy Under Model Uncertainty in a Small Model of the US Economy." *Macroeconomic Dynamics* 6 (1): 85–110.

Orphanides, A. 2003. "Monetary Policy Evaluation with Noisy Information." *Journal of Monetary Economics 50* (3): 605–631.

Orphanides, A. 2001. "Monetary Policy Rules Based on Real-Time Data." *American Economic Review* 91 (4): 964–985.

Orphanides, A. and S. van Norden. 2002. "The Unreliability of Output-Gap Estimates in Real Time." *Review of Economics and Statistics 84* (4): 569–583.

Orphanides, A. and V. Wieland. 2000. "Inflation Zone Targeting." *European Economic Review* 44 (7): 1,351–1,387.

Orphanides, A. and J. C. Williams. 2007. "Robust Monetary Policy with Imperfect Knowledge." *Journal of Monetary Economics* 54 (5): 1,406–1,435.

Primiceri, G. E. 2005. "Time Varying Structural Vector Autoregressions and Monetary Policy." *Review of Economic Studies* 72 (3): 821–852.

Rubbo, E. 2020. "Networks, Phillips Curves, and Monetary Policy." Working Paper.

Rose, D. 1988. "The NAIRU in Canada: Concepts, Determinants and Estimates." Bank of Canada Technical Report No. 50.

Sack, B. P. 1998. "Uncertainty, Learning, and Gradual Monetary Policy." *Finance and Economics Discussion Series* 1998-34.

Sack, B. P. and V. Wieland. 2000. "Interest-Rate Smoothing and Optimal Monetary Policy: A Review of Recent Empirical Evidence." *Journal of Economics and Business* 52 (1–2): 205–228.

Schaling, E. 2004. "The Nonlinear Phillips Curve and Inflation Forecast Targeting: Symmetric Versus Asymmetric Monetary Policy Rules." *Journal of Money, Credit and Banking* 36 (3): 361–386.

Schmidt-Hebbel, K. and C. E. Walsh. 2009. "Monetary Policy Under Uncertainty and Learning: An Overview," in *Central Banking, Analysis, and Economic Policies Book Series* 13, eds. Klaus Schmidt-Hebbel, Carl E. Walsh and Norman Loayza (Central Bank of Chile) Chapter 1: 1–25.

Setterfield, M., D. Gordon and L. Osberg. 1992 "Searching for a Will o' the Wisp: An Empirical Study of the NAIRU in Canada." *European Economic Review*, 36, 119–36.

Söderström, U. 2002. "Monetary Policy with Uncertain Parameters." *Scandinavian Journal of Economics* 104 (1): 125–145.

Staiger, D., J. H. Stock and M. W. Watson. 1997. "The NAIRU, Unemployment and Monetary Policy." *Journal of Economic Perspectives 11* (1): 33–49.

Stock, J. H. and M. W. Watson. 2009. "Phillips Curve Inflation Forecasts." *Understanding Inflation and the Implications for Monetary Policy*, eds. Jeffrey Fuhrer, Yolanda Kodrzycki, Jane Little and Giovanni Olivei (Cambridge: MIT Press).

Svensson, L. E. O. 1997. "Inflation Forecast Targeting: Implementing and Monitoring Inflation Targets." *European Economic Review* 41 (6): 1,111–1,146.

Svensson, L. E.O. 2017. "What Rule for the Federal Reserve? Forecast Targeting." National Bureau of Economic Research Working Paper No. 23993.

Svensson, L. E. O. and N. Williams. 2008. "Optimal Monetary Policy Under Uncertainty: A Markov Jump-Linear-Quadratic Approach." *Federal Reserve Bank of St. Louis Review* 90 (4): 275–293.

Tesfaselassie, M. F., E. Schaling and S. Eijffinger. 2011. "Learning About the Term Structure and Optimal Rules for Inflation Targeting." *Journal of Money, Credit and Banking* 43 (8): 1,685–1,706.

Tetlow, R. J. and P. von zur Muehlen. 2001. "Robust Monetary Policy with Misspecified Models: Does Model Uncertainty Always Call for Attenuated Policy?" *Journal of Economic Dynamics and Control* 25 (6–7): 911–949.

Tkacz, G. 2010. "An Uncertain Past: Data Revisions and Monetary Policy in Canada." Bank of Canada *Review* (Spring): 41–51.

Vinci, F. and O. Licandro. 2020. "Switching-Track After the Great Recession." University of Nottingham Discussion Paper No. 2020/02.

Walsh, C. E. 2004. "Implications of a Changing Economic Structure for the Strategy of Monetary Policy." University of California at Santa Cruz SCCIE Working Paper 03-18.

Wieland, V. 2000. "Monetary Policy, Parameter Uncertainty and Optimal Learning." *Journal of Monetary Economics* 46 (1): 199–228.

Wieland, V. 2006. "Monetary Policy and Uncertainty about the Natural Unemployment Rate: Brainard-Style Conservatism Versus Experimental Activism." *B.E. Journal of Macroeconomics* 6 (1): 1–34.

Williams, J. C. 2013. "A Defense of Moderation in Monetary Policy." *Journal of Macroeconomics*, 38, 137–150.

Yellen, J. L. 2017. "Inflation, Uncertainty, and Monetary Policy". *Business Economics*, 52(4), 194–207.

Yetman, J. 2000. "Probing Potential Output: Monetary Policy, Credibility, and Optimal Learning under Uncertainty." Bank of Canada Staff Working Paper No. 2000-10.