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Central Bank Digital Currency: a Review and Some Macro-Financial Implications

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Abstract

Central Bank Digital Currency (CBDC) has become a major policy interest among global central banks. However, its introduction faces many challenges including those that are legal, technological and political in nature. In this paper, we summarize those challenges and add a few more that have not received much attention in the literature. Relying on the historical evidence of past episodes of financial innovation we explore the hypothetical impact of CBDC based on institutionalist hypothesis and McCallum's rule of money growth which is well suited to studying the possible macroeconomic impact of CBDC. According to our simulations, the introduction of CBDC need not pose an inflation control problem but financial stability issues aren't fully offset. We also provide some policy implications.

Keywords: Central Bank Digital Currency, Velocity, Money Demand, Monetary Policy, McCallum Rule
JEL classification: O31, O33, E41, E42, E51, E52, E54

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"You can see the computer age everywhere but in the productivity statistics." (Solow 1987)

1. Introduction

The last decade or so will be partly remembered in history as disruptive because of a series of crises, two financial in nature and one health related, occurring at a time of rapid growth in computing technology.[1] While Solow's aphorism may well be correct for some countries his view does not detract from the fact that, in the monetary sphere, an emerging bout of "creative destruction" is underway.[2] This is exemplified by the proliferation and growing sophistication of various forms of electronic payments. From these discussions emerged increased focus on central bank digital currency (CBDC).

Several authors have already highlighted some confusion surrounding how to define CBDC (e.g., Meaning et. al. 2018). To be clear, in this paper we are interested in a digital currency issued by the central bank that complements the traditional role of supplying notes and coins in circulation thereby allowing the possibility that some features associated with digital technology, to be described later, can also be added. Specifically, we are interested in the macroeconomic functions of CBDC that might be used by the general public.[3] We do not, however, consider the case of cryptocurrencies.[4] The availability of currency in digital form raises the possibility that central banks can become more akin to commercial banks if, for example, individuals are permitted to hold balances at the central bank or compensate the holders of CBDC.

[1] For example, the iPhone was introduced in 2007, the same year that some chronologies date the beginning of events that would become known as the Great or Global Financial Crisis (GFC) of 2008-9. Anderton et. al. (2020) provide a detailed and useful summary of the general challenges of the digitalisation of the economy with emphasis on implications for the European Union. Haldane (2020) also provides a nice summary of the various technological forces at play.

[2] Solow's quip originates from a book review (Solow 1987) in which he also writes: "…what everyone feels is a technical revolution, …has been accompanied everywhere… by a slowdown in productivity growth, not by a step up." The term is associated, of course, with the work of Schumpeter and, succinctly, refers to "…process of industrial mutation that continuously revolutionizes the economic structure from within, incessantly destroying the old one, incessantly creating a new one…".

[3] This is distinct from w-CBDC, that is, digital money used to settle large or wholesale transactions. The Swiss National Bank is already experimenting with this form of payment (see SNB 2020).

[4] There is, occasionally, confusion between CBDC and stablecoins. The latter are created by the private sector and may be backed by physical assets (e.g., gold), or financial assets (e.g., dollars), existing cryptocurrencies, or can be unbacked. Other than the moral hazard raised by the possibility that the central bank may be involved in a bail-out of some kind there are, in principle, no financial stability implications from stablecoins. In contrast, CBDC, as we shall note later, can have financial stability implications. See BIS (2019) and Barontini and Holden (2019) for additional details.

Why the surge of interest in CBDC? One under-appreciated factor is perhaps the speed with which interest in a digital currency has attracted attention from central banks, despite resistance in some quarters and the theoretical possibility noted by economists long ago.[5] Next, central banks in both advanced and emerging market economies largely see eye to eye about motivations for adopting CBDC with financial stability and monetary policy considerations topping the list, based on a recent survey (e.g., see Boar et. al., 2020).[6]

What remains contentious is the impact of CBDC on the conduct of monetary policy and the monetary transmission mechanism. Given that the last decade has also seen much greater and more frequent interventions by central banks in financial markets, generally referred to as unconventional monetary policy (UMP; e.g., see Lombardi et. al. (2019) for a survey), the prospect of CBDC opens up an alternative avenue some observers contend take central banks more deeply into the realm of fiscal policy and credit allocation. Indeed, a potential advantage of digital forms of currency is that they represent a vehicle to overcome the zero lower bound of interest rates (ZLB; e.g., Rogoff, 2017b, Bordo and Levin, 2018).

There has been a proliferation of papers dealing with the practical, technical, and legal issues surrounding the introduction of CBDC, as well as some theoretical studies that examine the hypothetical financial and macroeconomic impact of CBDC. Our paper, however, is the first to rely on historical data to consider the range of inflationary effects of the most likely forms of CBDC to be introduced by the major central banks in the foreseeable future.

In doing so, we revive some parts of the literature on velocity of circulation to show that periods of rapid financial change are not new and that an historical understanding of institutional factors may be helpful to determine whether inflation control can be retained once CBDC are

[5] The case of the US Federal Reserve comes to mind. This may be slowly changing (Brainard (2020a, 2020b) though caution remains (e.g., as recently underscored by Fed Chair Jay Powell; see https://meetings.imf.org/en/2020/Annual/Schedule/2020/10/19/imf-cross-border-payments-a-vision-for-the-future). For proposals that presage central bank involvement directly with the public see Barrdear and Kumhof (2016) and references therein.

[6] Other motivating factors include as a vehicle for raising financial inclusion, improving the efficiency of payments systems, reducing the costs and facilitating cross-border payments, and mitigating illegal financial activities.

introduced. The pandemic, and the potential for CBDC as an instrument of monetary policy has already attracted attention outside central banks (e.g., see Godbole, 2020). Next, we propose simple simulations based on McCallum's policy rule (1988). McCallum's rule is unencumbered by the ZLB and it also has the virtue of shifting focus to the central bank's balance sheet. After all, as many have pointed out, in its most neutral form CBDC changes the composition but not the size of the balance sheet. However, it is the potential of CBDC to change the balance sheet of the central bank that has generated interest from several quarters. Since the GFC attention has focused on the balance sheet of the monetary authorities thanks to the growing reliance on unconventional monetary policies (e.g., see Lombardi et. al., 2019, and references therein). McCallum's rule, which can be specified for any definition of a monetary aggregate, is used to simulate scenarios of different monetary policy stances in an environment where financial innovations take place. We rely on the history of rapid technological developments in transactions technologies to determine hypothetical future inflation paths and consequences for money growth.

The rest of the paper is organised as follows. Section 2 considers the wide array of issues, both legal and policy-related, arising from the prospect of introducing CBDC. The discussion then focuses on the issues of greatest relevance to this paper, namely some of the monetary policy implications of CBDC. Section 3 considers institutional and historical evidence that might be informative about the consequences of introducing CBDC in part by revisiting a literature abandoned some time ago but one that may offer some clues about the consequences of the latest trends in payments innovations, namely money demand and the velocity of circulation. Next, we provide some simulation results suggestive of the potential for CBDC to act as a vehicle to control inflation. We conclude that CBDC need not impair inflation control nor are all financial stability implications overcome by the introduction of a digital form of money. Section 4 concludes by summarizing our findings and indicating a few questions left for future research. Other things being equal, the regulatory and institutional environments will dictate the macroeconomic effects of CBDC.

2. Framing the Issues: A Literature Survey

(a) A Wide Range of Related Questions and Issues

While the principal objective of our study is to address the monetary policy and monetary transmission mechanism implications of CBDC it is useful to take a step back and ask how a technological development involving an ostensibly small segment of the monetary system in some countries is thought by some to herald a potentially new era in monetary policy and financial stability.[7] Others have also taken a "big picture" approach to our understanding of the implications of CBDC. A partial list includes Rogoff (2017a), Bordo and Levin (2018), Davoodalhosseini and Rivardeneyra (2018), and Brunnermeier et. al. (2019b). As will become evident below, there is foment in theoretical approaches to the problem while, empirically, we suffer from largely absent data which seemingly renders history of little help in understanding the principal forces at play. As we shall see history does provide some useful clues about the potential impact of CBDC.

Difficulties emerge when one is confronted with the question of how to define or measure "money". While the issue is an important one, and we do not wish to downplay it, space limitations require us in what follows to consider only the narrow and broad money concepts. The former typically consists of notes and currency that circulate outside the banking system and reserves held at the central bank inside the banking system. This is also called base money. However, since regulatory and other changes in financial structure in several countries have done away with required reserves for decades, base money as it is traditionally defined, is no longer as relevant as it used to be.[8] Similarly, the sheer variety of definitions of broad money make it difficult to rely on a broad monetary aggregate that is defined precisely in the same manner

[7] Typically, the ratio of currency to broad money (or to GDP) is an indicator of the relative importance of notes and coins. While this ratio has fallen in several advanced economies, notably Sweden, Great Britain, Norway, and showed signs of falling in others until the late 1980s (e.g., Australia, Canada, Switzerland, and the United States) it has risen or remained stable for the last few years. Similar, though less dramatic, experiences are observed in several emerging market economies. See the *Appendix*. We return briefly later in the paper to some of the forces at play with implications for CBDC. Ashworth and Goodhart (2020) have noted a similar revival in the fortunes of paper currency holdings in the US, the UK, Japan and Switzerland. Studies and surveys conducted in a variety of advanced economies conclude that cash remains important and that the public is reluctant to abandon it completely. Unsurprisingly, demographic characteristics also play a role. Inter alia, also see Otani and Suzuki (2008), Huynh et. al. (2020), and Flannigan and Parsons (2018).

[8] Although the International Monetary Fund continues to publish base to (broad) money ratios and base growth series in *international Financial Statistics* only the currency component is, strictly speaking, fully comparable across countries. There are differences in definitions in the remaining components of the monetary base though the IMF strives to ensure international comparability. See IMF (2016, pp. 197-200).

across countries. The best that can be said is that broad money consists of narrow money and a set of highly liquid financial assets booked in the regulated (i.e., typically commercial) financial system.[9]

Traditional theory has money fulfilling three functions. They are: the unit or medium of account function,[10] the medium of exchange function, and the store of value function. Monetary theory has often struggled to find reasons to explain why individuals hold money and, in particular, the respective roles played by inside and outside money. The relevant literature, going back at least to Gurley and Shaw (1960), underscored the differences between money created by central banks (outside money) and money that resides in (commercial) banks and, through a combination of regulation and multiplier effects, contributed to influence economic activity. We have no desire to revive the debate (see, however, Lagos, 2008, and references therein) but only note that at least one element is directly relevant to the debate over introducing CBDC, namely that it has the potential of blurring the distinction between central banks and commercial banks and, hence, potentially impact the conduct of monetary policy.

At least two theoretical strands have, over the past several years, returned or emerged to tackle the potential role and significance of CBDC. One generally referred to as the "new monetarist" theory (e.g., see Lagos et. al., 2017) is grounded in the micro-foundations of money and asks what motivates transactions using an asset with the functions ascribed to money in the presence of costly frictions (e.g., search). One of the monetary policy implications of this theoretical approach is that some inflation is desirable, but money's existence is not supported as independently providing utility to individuals.

[9] Monetary aggregates are typically obtained by summing various financial assets with differing degrees of moneyness. Attempts at weighting various components of existing monetary aggregates proved popular for a time in the form of Divisia monetary aggregates (Barnett, 1980, inspired by Diewert, 1976) subsequently re-branded as monetary services indices. While some are still published most have been discontinued in part because of the decline in the profession in the predictive role of monetary aggregates even if they retain some of their power to do so (e.g., see Siklos and Barton, 2001, and references therein).

[10] The medium of account function is more accurate since some physical item, be it gold or some other metal, or paper, has typically served as "money". Yet, some assets are expressed in monetary units even if they do not circulate (e.g., Special Drawing Rights issued by the International Monetary Fund). In a digital world, the distinctions can become even less clear.

An older approach, resurrected from some of the implications of individuals choosing to hold traditional forms of narrow money versus ones in digital form, stems from Diamond and Dybvig's (1983) seminal bank run model which can be useful in developing an understanding of the implications of CBDC in a world where markets are subject to disruption due to financial innovations. The focus here is on the liquidity of monetary assets and the role of trust and confidence in banking institutions to ensure that transactions are settled. This is particularly relevant when considering the risk characteristics of various assets. It is conceivable according to this theory and, depending on the specific design of CBDC, that individuals may not view digital equivalents to conventional notes and coins as risk-free.[11]

Other theoretical approaches that have sought to provide insights into the consequences of introducing CBDC into existing monetary systems have also been brought to bear on the problem. These include cash-in-advance models, where money is essential to buy goods and services and must therefore be held by individuals, or models where two different assets with monetary characteristics circulate side-by-side (Kiyotaki and Wright, 1989), as well as overlapping generations models (Kim and Kwon, 2019). The former is relevant to the CBDC debate because of the potential for narrow money to possess some of the characteristics of inside money. The latter may be useful, for example, in considering the impact of the adoption of CBDC by some groups while others persist or prefer to hold more traditional forms of currency.

The bottom line, however, is that guidance about the impact of CBDC on monetary policy and monetary transmission mechanisms is, to date, limited. Niepelt (2020) summarizes the problem as one where theory is inadequate in providing points of departure that can inform policy makers about the consequences of introducing CBDC. "…the discussion about digital central bank money could benefit from well-articulated, coherent, formal models that clarify equivalence relations…" (op.cit., p. 233).[12]

[11] It is common to assume, for example, that US Treasuries are essentially risk-free assets. However, as is now well-known, this normally highly liquid market experienced considerable stress in early March 2020 as the pandemic's economic and financial consequences became rapidly magnified. See, for example, Cheng et. al. (2020). The crisis was addressed only when the Federal Reserve intervened heavily in U.S. Treasuries. The bottom line, however, is that classes of financial assets once deemed risk-free may contain more risk than previously thought.

[12] A classic example of an irrelevance or equivalence proposition is the Modigliani-Miller theorem which states that, in an efficient market with no transaction costs, taxes, or agency costs, the value of a firm is not affected by whether it is financed by selling debt or equity. Reality, of course, contradicts these assumptions. Another example is the

Perhaps one reason the potential introduction of CBDC has attracted so much attention are the legal, technical, and political-economy implications associated with this development. We consider briefly each one in turn. As noted previously, a CBDC that combines the potential for individuals to hold balances at the central bank and to earn interest on these balances brings the central bank closer to some of the tasks currently performed by commercial banks.[13]

Economists will note, of course, that central banks often began their existence with functions that intersected ones carried out by commercial banks and that private and government note issues have circulated side-by-side (e.g., Eichengreen, 2019, Fung et. al., 2018, Goodhart, 1988, and Henckel et. al., 1999)). As central banks have evolved legislation has tended to place limitations on the ability of the monetary authority to compete directly with depository institutions. We return to this issue in the next section. A large number of authors have also raised a potential externality from CBDC for the commercial banking sector (see, inter alia, Rogoff, 2017a, Bordo and Levin, 2018, and Brunnermeier and Niepelt, 2019, Fernández-Villaverde et. al., 2020). Indeed, the challenges arising from innovations in financial technology more generally are not new. For example, on the eve of the new millennium, former Bank of England Governor Mervyn King mused that digital transactions offered the possibility of any security to be settled in real time (King, 1999).

Consequently, in assessing the economic implications from the introduction of a digital currency, the design of CBDC is not innocuous. For example, the distinction between retail and wholesale forms of CBDC is important. Also critical are the uses for which CBDC are designed.[14]

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concept of Ricardian equivalence which defines conditions under which debt-financed spending today will fail to stimulate economic activity because it is treated by individuals as a deferred tax. The theory is viewed as being implausible in explaining the long-run impact of government borrowing.

[13] The relevant literature often does not make clear that commercial banks offer more than just interest income to their customers. They offer a wide variety of services and proposals to create CBDC never suggest that central banks are planning to emulate all the complementary services offered by banks. For example, by 2003, that is, well before the GFC, US banks generated almost half of their income from non-interest sources (De Young and Rice, 2004). Interestingly, this ratio has declined since to about a third of operating revenue and Haubrich and Young (2019) conclude this reflects a reaction to the falling out of favour of securitization. Brunnermeier et. al. (2019b) find that non-interest income and systemic risk co-vary for US banks. If the foregoing trends are international in nature, then this provides another avenue for CBDC to potentially impact financial stability risks.

[14] Auer and Böhme (2020) provide a helpful device in the form of a pyramid to illustrate the connection between the needs CBDC will satisfy from the consumers' perspective and the design of the digital instrument.

Moreover, CBDC also has financial stability implications. Therefore, in principle, legal arrangements can be defined that can mitigate the negative externalities for commercial banks that could excessively impinge on their ability to compete.[15] In what follows, we do not concern ourselves with this implication and consider the case where CBDC takes on features that notes and coins currently do not offer precisely because there is the potential for social benefits, including an impact on monetary policy, from the shift to a digital currency.

Turning to technical aspects of CBDC we note that much has been made about how their introduction may improve the efficiency and safety of payments systems (e.g., BIS, 2020a, 2020b). Indeed, central banks such as the Bank of Japan and the ECB have underscored the payments dimension of the digitization of the economy.[16] To the extent that CBDC can improve oversight and provide a safety net of sorts for payments systems that are now, globally, overwhelmingly digital in nature, remains to be seen. What is sometimes under-appreciated are the potential challenges from a shift to a cashless world. One is cultural, the other technical in nature. The cultural one comes from the well-known preference in some societies for conventional notes and coins (e.g., as in Japan, Germany, Switzerland, and the US; see also below). Indeed, as noted previously, the shift to holding more notes and coins in some advanced economies has been notable (see the *Appendix*).[17] Even in societies where the shift to a digital currency is much more advanced (e.g., Sweden) policy makers have been led to further study the

[15] Concerns about central banks infringing on market contestability (e.g., see Engert and Fung, 2017) must confront the growth of Fintech (financial technology) together with the rapid increase in the fraction of the population that uses the Internet and has broadband subscriptions. Using World Bank data (see *Appendix*) these developments are global in nature and not restricted to advanced economies alone. Garcia et. al. (2020) argue that the most basic form of CBDC (i.e., with no commercial banking characteristics) would impact bank profitability. However, the authors make the heroic assumptions that CBDC is adopted in one quarter and that banks will not pass on increases in costs to consumers.

[16] See ECB (2020), And Kihara and Wada (2020).

[17] An important factor in the drive to introduce CBDC is the desire to combat corruption and illicit activities (e.g., Rogoff 2017a, Nuno, 2018). These concerns are highlighted by the observation that the data reveal growth in the holding of large denomination notes. An example is the European Central Bank's phasing out of the 500 euro note in response to some of these concerns. Ashworth and Goodhart (2020) also remarked on the holding of large versus small denomination notes. A difficulty in assessing the significance of this problem is that the interpretation of the data is sensitive according to whether measurement is on a per capita or as a percent of the total value of notes and coins in circulation. The interpretation is also a function of how one classifies large versus small denomination notes. Data in the *Appendix* illustrates the problem and points to the problem of a rise in large denomination note holdings on a per capita basis. The same is less clear-cut on the value metric. The ongoing coronavirus pandemic is beginning to reveal that large denomination notes may also be held for precautionary purposes (see Chen et. al. 2020).

consequences of the digitalization process (e.g., see Alderman, 2018).[18] Readers should also be reminded that, globally, there exist a large number of networks, not all equal in terms of their readiness for real-time settlement. Readiness is a desirable objective given that settlement in cash is final.[19] This is on top of retail payment systems where delays in settlement imply some residual risk, at least relative to cash. Whether these risks are small enough to be ignored is a different issue we do not consider nor whether cyber risks, and the capacity of the authorities to counteract them, also imply risks to the introduction of CBDC that may not be present with conventional notes and coins.

It is sometimes forgotten that the introduction of CBDC would take place in an environment where a proliferation of other forms of electronic and digital payments have become commonplace. For example, credit and debit cards, not to mention other forms of payment such as cash or gift cards, have become popular and are used widely. Moreover, one should not lose sight of the fact that commercial banks, and their non-bank competitors, have also adapted to technology under the existing notes and coins environment through the spread of automatic teller machines (ATM) which have, over time, gone beyond simply dispensing cash.[20] Indeed, networks have emerged (e.g., Interac in Canada, China UnionPay in China, STAR in the United States, LINK in the UK) that facilitate obtaining funds both domestically and abroad. It is not inconceivable that these will adapt to new future needs including some involvement with some forms of CBDC.

[18] The age profile of the population is also a factor. Indeed, age dependency is rising in both advanced and emerging market economies (see the *Appendix*). Whether resistance to CBDC is a cultural phenomenon or a failure of policy makers to explain the net (social) benefits of CBDC remains an open question.

[19] The authorities are aware of the need for "interoperability" and, at least in 2016, domestic interoperability between retail and wholesale systems is common in advanced economies while cross-border interoperability is still a work in progress (see Tompkins and Olivares, 2016). Also, see Auer et. al. (2020) for an overview of the technical architecture of CBDC.

[20] Data from the World Bank (see *Appendix*) suggest stability or modest increases only in the number of ATMs in the advanced economies surveyed while many of the largest EMEs have seen sharp increases in ATMs. Once again Sweden is somewhat of an exception as the number of ATMs has seen a steady drop since 2011. Similarly, based on BIS data, the number of cards (cash, debit, and credit) issued has remained steady in AEs while rising quickly in most EMEs though the average number of cards held, per capita, is considerably smaller in EMEs than in the AEs surveyed. The *Appendix* contains some of the details. After a draft of the paper was written some of the data of the kind used in our study have recently been combined to create an index to signal how seriously central banks are treating the digitization of currency. See Auer et. al. (2020).

One curious omission in the debate over the various facets of CBDC introduction and management (see G30 (2020), Arner et. al. (2020), Kiff et. al. (2020), and Allen et. al. (2020), Bank of England 2020) is that they tend to ignore or downplay the problem of data storage. Using digital forms of payment requires that balances in CBDC be stored somewhere. The idea of centralizing such storage raises all sorts of risks, from privacy to security, but even if storage is decentralized[21] the sheer size of storage required, not to mention its durability, are details that have not been adequately addressed to date.[22] Indeed, as has been pointed out to us, these considerations, combined with the form of CBDC that is eventually introduced (i.e., token or account based) will also influence how the introduction of digital currencies will impact the supply of money.

Finally, one should not underestimate the challenges posed by the political-economy implications from the introduction of CBDC. Some issues have already been alluded to, namely the potential for CBDC to improve financial inclusion, a goal normally outside that of conventional central banking,[23] the risks to monetary sovereignty or in the status of global reserve currencies, as well as the independence of central banks not only from governments but from the commercial banking sector and, lastly but just as important, the loss of anonymity that cash transactions provide.[24] Indeed, in a first report published by a consortium of central banks (Bank of Canada et. al. 2020) complete anonymity for CBDC is deemed "not plausible".

[21] If this is done across borders, then potentially sovereignty related questions will also emerge.

[22] The question of storage and durability is inspired by challenges faced in other fields as in physics, notably the storage of data generated by CERN (European Council for Nuclear Research), and the life expectancy of current technology which is far less than that of conventional paper or polymer notes.

[23] But one that more central banks have begun to publicly mention in response to evidence about links between monetary policy and inequality (e.g., Coibion et. al., 2017). Data from the World Bank Development Indicators (see the *Appendix*) reveal a tendency for the income share of the bottom 20% of the distribution to have fallen in advanced economies while the opposite trend is more apparent among EMEs. Furthermore, bank account ownership among the poorest 40% of the population has tended to rise in EMEs and remain stable in AEs. After the first draft of this paper was written the IMF introduced an index of financial inclusion (Sahay et. al., 2020) that includes many of the indicators shown in the *Appendix* and mentioned here and elsewhere in the paper.

[24] The loss of anonymity has frequently been raised as a critical issue. To be sure, most individuals and business, for practical reasons, to economise on some of costs associated with the adoption of new technologies, cultural factors, the desire by a few to preserve the opportunity to conduct illicit transactions, will always prefer cash. Yet, the proliferation of online and card use, not to mention smartphones, also suggests that some of these concerns are overblown (e.g., see Warzel and Thompson, 2019). Indeed, cards and smartphones underscore the role that "loyalty" plays in transactions technology (e.g., see Amamiya, 2019). Japan is one, but not the only example, where government intervention also skews the technology adopted for payment. A fascinating experiment was undertaken in Japan in 2019 when, to blunt the impact of the recent rise in the consumption tax from 8% to 10%, the fiscal authorities favoured digital transactions through a discount program. Given the current predicament the Bank of

Other than the challenge to central bank independence, and its potential to further disrupt the conduct of monetary policy, to which we next turn, we will not consider the others discussed above to preserve our focus on the macroeconomic consequences of CBDC.

(b) Monetary Policy and Financial Stability Considerations

Next, we move onto more "practical" questions associated with CBDC and its implications for the conduct of monetary policy. The GFC, and now spurred on further by the ongoing coronavirus pandemic, has enhanced the potential for CBDC to have monetary policy effects since it is seen as an additional instrument that helps overcome the reduction in the effectiveness of conventional monetary policy at the zero or effective lower bounds (ELB).[25] The image of a central bank, via CBDC, containing interest and deposit-taking components that can engage in a form of QE for all is viewed as an instrument that delivers stimulus quickly and potentially persistently. CBDC can therefore be considered an additional safe asset (e.g., US dollars) that is prone to shortage during crisis conditions. Haldane (2015), Rogoff (2017a), and Meaning et. al. (2018) are just some of the authors who have raised these issues. The issue is not unrelated to the role CBDC can play in cross-border payments which may become one of the most contentious in the debate.[26] Although, strictly speaking, outside the scope of this paper, we return to the topic in the conclusions.

It is reasonable to ask whether introducing a financial asset, whose share is modest in the universe of liquid and safe assets, can make such a difference. The simple answer is that we do not yet know. However, by way of an analogy, central banks intervene in foreign exchange rate

Japan's monetary policy finds itself in this development also has monetary implications. See https://www.nippon.com/en/japan-data/h00537/smart-shopping-reward-points-and-consumption-tax-hike-exemptions-a-bargain-for-consumers-i.html. We are grateful to Jouchi Nakajima of the Bank of Japan for bringing this episode to our attention. Nevertheless, central banks are keenly aware of the issues, but the bottom line is that no technology is able yet to provide foolproof anonymity with digital transactions. Darbha and Arora (2020) clearly outline the technical challenges but also see Bindseil (2020) and Shirai (2019).

[25] Needless to say, not everyone shares this opinion. Lombardi et. al. (2018) and references therein consider both sides of the debate. For example, Lombardi et. al. (2019; see also references therein) suggest that monetary policy retains some effectiveness even at the ELB.

[26] The G20 has made cross-border payments a priority in 2020. The Financial Stability Board has published a roadmap to assist policy makers. See FSB (2020).

markets and, while the amounts are dwarfed by the size of the market, there is little doubt that exchange rate levels and volatility can be impacted, even if only temporarily.

More importantly, the potential for CBDC to bring monetary policy closer to individuals raises an issue that reared its head in reaction to the GFC, that is, the blurring of fiscal and monetary policies. In particular, one concern is whether it is appropriate for the central bank to become involved in credit allocation. The sharp rise in the size of central bank balance sheets in the wake of the GFC was, at first, largely restricted to the economies most directly affected by the crisis. The pandemic has led to many more central banks, even in emerging markets, to adopt unconventional monetary policies. Policies, both of the fiscal and monetary varieties, in response to the economic fallout from the ongoing pandemic, necessitated interventions from central banks on a global scale. For some the reaction is seen as the proper role of a central bank whose policy should be compatible with fiscal policy. Others see the expanded role of the central bank as potentially problematic.

How then can some empirical evidence be brought to bear on the issue when CBDC effectively are on the drawing board but not in circulation? In this connection the investment made by central banks in developing DSGE models is fortuitous given that such models are well suited to asking “what if” questions (e.g., Barrdear and Kumhof, 2016). But, as we shall see, monetary history can also provide insights.

On the empirical dimension, the arrival of CBDC may well lead to a resurgence of interest of putting “money” back into monetary policy. Indeed, the growing number of central banks at the ELB, and renewed interest in the liquidity trap,[27] offers an opportunity to examine the potential macroeconomic impact of CBDC. Indeed, history offers an alternative perspective. In recent decades assessments of the stance of monetary policy have focused on the behaviour of central bank policy rates. This has been further reinforced by the widespread reliance on the Taylor rule as a means of describing the conduct of monetary policy. A casualty was the relegation of money demand into the background of policy discussions.

[27] Though not directly dealing with the potential for CBDC Lhuissier et. al. (2020) and Siklos (2020) empirically consider the liquidity trap issue.

Although there have been some attempts to revive the topic of stability in money demand (e.g., see Benati et. al., 2018, Lucas and Nicolini, 2015), some of the debate has also revolved around questions noted earlier such as how to define monetary aggregates.[28] Another reason behind the resurgence of interest has to do with interest rates at or near the ELB, and likely to remain so in a growing number of economies, since this changes, at least from a theoretical perspective, the impact of QE, especially if it is directly delivered to households. Notably absent, however, from much of the discussion is the role of the velocity of circulation where theory and earlier empirical evidence offers an explanation for how financial innovations can provide a mechanism for stability. The so-called institutionalist hypothesis of velocity (Bordo and Jonung, 1981, 1987) is a vehicle that explains how technological changes in payments systems, improved communications, and changes in the services offered by banks, impact velocity. Modern time series analysis later highlighted how financial innovations could create stability in the long-run behaviour of velocity where traditional specifications, mirrored in conventional money demand functions, could not (Siklos, 1993). We revisit this literature to consider the potential role of CBDC.

Beyond the traditional monetary policy functions of money, the introduction of CBDC provides a potential treatment for financial stability risks. The mitigation of financial stability risks was ranked first as the motivation for central banks studying the possible introduction of CBDC (Boar et. al. 2020). For example, if CBDC have deposit and interest rate characteristics, the central bank can use these to ensure that there is sufficient liquidity when crisis conditions would otherwise lead to a flight to quality. This stems from the safe asset characteristic of CBDC. Alternatively, CBDC is interpreted as consistent with the central bank's traditional role as a lender of last resort but in a new guise (e.g., see Henckel et. al., 1999, Armelius et. al., 2020). Moreover, as noted previously, CBDC may provide some underpinnings to ensure the smooth and secure functioning of the payments system. However, given the existence of a large number and variety of systems the technical elements required to improve the quality of payments

[28] Another consideration is whether conventional money demand specifications, determined by an interest rate, ought to be modelled in log-log form, that is in the logarithm of the interest rate, or in semi-log form, namely in interest rate levels. A fuller discussion is beyond the scope of this paper. See, however, Benati et. al. (2018), and Ireland (2009).

systems appears daunting. Regardless of the uses and types of CBDC it is also clear that its imminent arrival places a new challenge on central banks by requiring formidable information technology (IT) to carry out its tasks, a point that seems insufficiently emphasised. This is surprising since the IT function is not only costly but generates additional security-related issues not normally associated with central banking. Perhaps this is one reason that central banks have emphasised the public-private partnership potential for CBDC (e.g., see Bank of Canada et. al., 2020, FSB 2020). Moreover, the fact that CBDC has sparked interest among many central banks (see Boar et. al. 2020) also highlights the need for international cooperation or coordination for the same reason that the GFC, and financial crises before that, led to the creation and raised the profile of the Financial Stability Board (FSB).[29]

3. Some Empirics

3.1 Institutional Change and Velocity Redux

CBDC may be viewed as the latest in a long line of financial innovations. Even if CBDC have not yet entered into circulation history may provide some insights if we look back at the impact of past financial innovations.

Mirroring money demand, velocity is traditionally thought to be a function of income and an opportunity cost of money (or other assets with money-like features). When the institutionalist hypothesis was proposed velocity in the long-run was driven, first, by increased monetization later to be overtaken by the growing sophistication of financial markets. Consequently, the secular behaviour of velocity would display a fall at first until the forces of technical change in finance and payments systems would reverse the direction of change and result in rising velocity. The largely U-shaped pattern observed by Bordo and Jonung (1981, 1987) reflects these forces. Ironically, around the time the hypothesis was introduced, a new wave of financial innovation was under way (see below).

[29] The FSB was created in the wake of the GFC to enhance regulation and supervision of the financial sector at the international level. See https://www.fsb.org/history-of-the-fsb/.

The following two equations help make clear the issues. Equation (1) describes a conventional model of velocity that mirrors standard money demand specifications. The institutionalist hypothesis adds a second vector of variables that seek to capture the role of financial innovations over time. The resulting specification is written as equation (2) below.

$$v_t = \delta_0 + \boldsymbol{\delta}_{\mathbf{j}} \boldsymbol{\Phi}_t + \varepsilon_{0t} \tag{1}$$

$$v_t = \beta_0 + \boldsymbol{\beta}_{\mathbf{j}} \boldsymbol{\Phi}_t + \boldsymbol{\beta}_{\mathbf{k}} \boldsymbol{\Omega}_t + \varepsilon_{1t} \tag{2}$$

where $\boldsymbol{\Phi}_t = \left[y_t^{pc}, i_t \right]'$, and $\boldsymbol{\Omega}_t = \left[CM_t, TNBFA_t, \pi_t^e \right]'$ are the vectors that drive velocity. The conventional model (1) requires only income (permanent income) and an interest rate (y,i), while the extended model (2) adds the currency-money ratio (CM), a proxy for financial innovation (total non-bank private loans to GDP or TNBFA), and expected inflation (π^e).[30] To economize on notation, equations (1) and (2) are understood to apply to each economy considered or to a cross-section of countries (i.e., panel).

The vector $\boldsymbol{\Phi}_t = \left[y_t^{pc}, i_t \right]'$ consists of the traditional variables believed to drive money demand, namely income and an opportunity cost proxy.[31] Income is theoretically expected to be negatively related to velocity while interest rates positively influence velocity. As empirical evidence mounted that relationships such as (1) broke down for a variety of reasons, ranging from definitions of the money supply not fit for purpose to a shift in emphasis at central banks to using an interest rate instrument to conduct monetary policy, came a noticeable decline in interest in the study of velocity and money demand. But interest did not disappear entirely and

[30] Originally (see Bordo and Jonung, 1981, 1987, and Siklos, 1993), the vector would also have consisted of the relative importance of the financial sector (e.g., total non-bank financial assets to total financial assets), the currency to broad money ratio, the proportion of the population in non-agricultural pursuits, and income volatility were also considered. In many economies, even emerging market economies, the fraction of the population living in urban areas has risen to a level that renders the proportion of the population involved in the agricultural sector an insignificant determinant especially in recent decades. The *appendix* shows a plot of the proportion of the population living in urban centres. Other than perhaps India, even emerging market economies are highly urbanized. As for income volatility the time series literature would move on to use a conditional volatility model (e.g., GARCH) to capture this kind of effect. Theory suggests a role for (real) permanent income, but this variable must be proxied since it is not observed.

[31] Important questions include how to measure opportunity cost and income variables. Space limitations prevent going into detail. However, this is a long-standing issue with a short-term interest rate and an aggregate income measure (e.g., GDP per capita) generally used in empirical work. See, for example, Laidler (1997). Many studies also include expected inflation because a nominal interest rate may not adequately capture the opportunity cost of holding money. In the empirical evidence shown below we include this variable. It is worth noting that, since the 1990s, inflation has been low and stable which would also help explain a decline in velocity (see below). The reduction in inflation is, of course, a global phenomenon that has been widely documented (e.g., see Ha et. al., 2019 and references therein).

there has been a small revival of interest and in empirical evidence suggestive that (1), where the dependent variable is expressed as real balances (i.e., a monetary aggregate deflated by prices) may be stable if proper account is taken in the definition of monetary aggregates to capture the impact of financial innovations (e.g., Lucas and Nicoloni, 2015) or if the focus remains on the long-run behaviour of money demand (e.g., see Benati et. al., 2018).[32]

Figure 1a reproduces, using more up to date definitions of income and money, the long-run pattern of velocity described above, at least until 1986, for five advanced economies that formed the basis for the institutionalist hypothesis and for the originally investigated sample in Siklos (1993). Conveniently, discussions are far-advanced about the potential introduction of CBDC in at least three of the countries shown (Canada, Sweden, and the UK) but are also topical in the US or Norway. The velocity series has been updated given that studies today rely on GDP as the proxy for income instead of GNP while broad monetary aggregates have also been updated since the early 1980s when there were fewer varieties of liquid assets.[33]

Figure 1b updates the data until 2016, using the same definition as in Figure 1a. We now observe a broad decline in velocity. However, it is worth again noting that the definitions of money aggregates, the denominator in the definition of velocity, include a wider array of liquid interest earning assets. In contrast, Figure 2 displays a measure of velocity based on a narrow monetary aggregate, essentially notes, coins, and chequable deposits. Rising velocity is now especially visible for Sweden and Norway beginning in the early 1990s. In the remaining three countries shown, velocity stalls from the middle to the end of the 1980s and then declines. Hence, the data reveal the impact of the shift away in some, but not all, advanced economies considered in their holdings of notes and coins. Velocity is comparatively stable in Canada, and in the US at least until the GFC. The gentle decline in velocity in the UK dates approximately from the early

[32] Another important element in the debate concerns whether the semi-logarithmic form of (1) is adequate as opposed to the log-log form (e.g., see Ireland 2008, Nakashima and Saito 2012). We retain the semi-logarithmic form, as did the earlier literature on velocity cited above, though all our conclusions are unchanged even when the log-log specification is used.

[33] The *appendix* contains a plot using the original data from Siklos (1993). There have been some changes in the definition of some of the monetary aggregates (M2 in Siklos, 1993) though they are still referred to as broad measures of the money supply. We were also able to add Australia, Japan, and Switzerland to the data set (not shown). All conclusions below were repeated for a panel that included these three additional countries with no impact on the main conclusions to follow (results not shown).

1990s, that is, around the time inflation targeting is introduced (1992) and following a noticeable acceleration in the aftermath of the financial "big bang" (1986).[34]

Turning to traditional determinants of velocity Figure 3a plots real per capita income on a normalized scale since the late 1980s while in Figure 3b central bank policy rates are shown for the same countries as in Figures 1 and 2. Other things being equal the rise in income would have contributed to reducing velocity (i.e., increase money demand) as would have the broad decline in interest rates shown in Figure 3b. These developments might explain some of the changes in velocity based on a narrow money aggregate as in Figure 2 but again only for Sweden and possibly Norway.

Figures 4 and 5 display two institutional determinants of velocity since 1871. However, as above, we focus on the period since the late 1980s. They are: in Figure 4, the currency-money ratio (CM), that is, notes and coins in circulation over the broad money measures used to calculate velocity (see Figure 1), and, in Figure 5, total loans to the private non-bank financial sector (TNBFA) as a percent of GDP. In three of the five countries the drop in CM shown in Figure 4 is consistent with the decline in velocity. For the US there is relative stability but a sudden change beginning with the GFC that only begins to be reversed in the last few years of the sample. Canada is the only exception though the pattern reflects a return of sorts to late 1970s levels. A similar temporary U-shape is not evident in the other countries considered.[35]

Another proxy for changes in the financial system, shown in Figure 5, is the share of total loans to the non-bank private sector as a percent of GDP.[36] To be sure, such a measure also captures the rising financialization of the economy, especially in the post-World War II era. However, to the extent that the rise in the series exhibited in all five economies shown also reflects the rise in the number of assets with money-like characteristics, then this would also presage a decline in

[34] There was also a sharp increase in the assets at financial institutions, as a percent of GDP, in the early 1990s owing to reforms to deposit insurance and the introduction of real time gross settlement. See Bowen et. al. (1999).
[35] The *Appendix* displays the CM proxy for the data originally used in Siklos (1993). As noted previously, despite changes in how the denominator of this indicator is measured, the two versions of CM compare well with each other.
[36] Unfortunately, the original variable used by Bordo and Jonung (1981, 1987) could not be updated.

velocity. Stated differently, the rise in loans would be reflected in the broad monetary aggregates used to calculate velocity.

The longer run trends described in (1) and (2) are nothing more than two potential cointegrating relationships. Hence, if cointegration is not obtained using (1) but is found using (2) this suggests that velocity's behaviour requires some indicator of financial development to obtain an equilibrium relationship. Of course, the finding of cointegration may be sensitive to the possibility of large shocks (i.e., breaks) or the fact that the behaviour of velocity has common features across several countries.[37] Equally important, if the addition of variables in (2) is necessary, this also suggests the potential for financial innovations such as CBDC to have macroeconomic relevance.

One may write the error correction form of (1) or (2) as follows:

$$\Delta v_t = \delta_0^{'} + \boldsymbol{\delta}_{\mathbf{j}}^{'} \Delta \boldsymbol{\Phi}_t + \boldsymbol{\delta}_{\mathbf{2}}^{'} \boldsymbol{\Sigma}_{t-1} + \varepsilon_{0t}^{'} \quad (1)'$$

$$\Delta v_t = \beta_0^{'} + \boldsymbol{\beta}_{\mathbf{j}}^{'} \Delta \boldsymbol{\Phi}_t + \boldsymbol{\beta}_{\mathbf{k}}^{'} \Delta \boldsymbol{\Omega}_t + \boldsymbol{\beta}_{\mathbf{1}}^{'} \boldsymbol{\Sigma}_{t-1}^{'} + \varepsilon_{1t}^{'} \quad (2)'$$

where Δ is the differencing operator, $\boldsymbol{\Sigma}$ are the error correction terms depending on how much cointegration is found,[38] and all other terms were previously defined. Equations (1)' and (2)' are vector error correction models. It is natural to ask whether the descriptions above generalize to other economies. The plots shown in Figure 6, for 19 economies, suggests that developments in velocity observed in Figure 1b is a global phenomenon and not restricted only to advanced economies.[39]

Next, we empirically establish whether cointegrating relationships described in (1) and (2) are obtained. We perform two sets of tests. First, we use the long-run data set shown in Figure 1. Table 1 presents several sets of cointegration test statistics. Part A of the Table shows test results for the conventional velocity equation (1) for the panel of five countries as well as each cross-

[37] Indeed, Bordo et. al. (1996) provide evidence suggestive of a 'North Atlantic' velocity function.
[38] For example, if there is only one cointegrating vector then the error correction term becomes a scalar.
[39] Interestingly, Uruguay is one exception to this phenomenon. It is also one of the few to have experimented with a digital currency. See, for example, Licandro (2018). Similarly, the decline in interest rates, albeit to levels that are relatively higher in emerging markets, is also observed in all the economies besides the ones examined in Figure 1. We relegate the relevant data to the *appendix*.

section; part B of the Table repeats the same exercise for the extended velocity model (equation (2)).[40]

The top portion of part A of Table 1 appears to suggest that there is evidence of common features in velocity thereby confirming and updating the evidence originally presented in Bordo et. al. (1996). When we turn to the individual cross-sections there is, at conventional significance levels, mixed evidence about the cointegration property for the conventional velocity model. In three of five countries shown the null of no cointegration cannot be rejected.[41] Turning to the extended model (part B of Table 1) the evidence is more convincing in favour of a finding of one or, at most, two cointegrating relationships whether the panel or the individual cross-sections are considered, with the possible exception of Sweden which, as we have already seen, stands out from the other countries considered. Hence, while cointegration between income, an interest rate and velocity may well describe the equilibrium relationship between these variables it is either mis-specified or requires additional variables to proxy changes in financial sophistication or institutional change.[42]

Figure 7 plots the fitted values from the estimated cointegrating relationships for all five countries since 1870, focusing on the case where there is a single cointegrating relationship. The left hand-side column shows estimates based on equation (1) while the right hand-side column plots the case for equation (2). In theory, the residuals (left hand-side scale) from the estimated cointegrating relationship should be stationary (that is, I(0)).[43] A visual comparison of the two sets of series illustrates that stationarity is found when the conventional velocity model (left hand-side) is augmented by proxies for financial innovations (right hand-side). Stated differently, deviations from stationarity are far more apparent in the conventional than in the extended velocity model.

[40] The tests results discussed below represent a mix of country-specific and panel estimates. The tables make the distinction clear. In the case of panels cross-section and time fixed effects are considered when statistical testing calls for this. Cross-section fixed effects are retained in the final specifications.
[41] Indeed, application of Hansen's alternative test for cointegration (the null is cointegration) is suggestive of the fragility of cointegration based on the conventional model for all five countries.
[42] The results in part B include expected inflation but the conclusions are unchanged when this variable is excluded. Indeed, estimates of the cointegrating vectors and the resulting estimates of the income and interest rate elasticities (not shown but see the *appendix*) suggest that inflation expectations are highly insignificant for all countries with the possible exception of Sweden.
[43] Indeed, the residuals, lagged one period, represent the error correction terms.

We also examine a broader set of economies, and a more recent but shorter sample. Cointegration, ideally, requires a long span of data and not only enough observations. Nevertheless, if we consider velocity for the economies shown in Figure 6 in a panel setting, there is a little bit of evidence that the variables in a conventional velocity model are not cointegrated while adding proxies for institutional change (e.g., income share of the poorest 20% of the population, number of mobile subscribers, number of secure internet servers) does yield a long-run or cointegrating relationship with velocity.[44] Once again we are led to the conclusion that the forces that produce the cointegration property are global in nature.

As noted above, the impact of financial innovation may take some time to show up in variables such as the velocity of circulation. In the present context this implies that the introduction and adoption of CBDC is also likely to take some time. Hence, its impact would span a long period of time. While the previous evidence is instructive because it demonstrates the important role played by institutional change, equilibrium in long-run velocity (and likely money demand), in a statistical sense, requires an explicit role for financial innovation, it remains unclear what the potential macroeconomic effects of CBDC might be. Accordingly, we now turn to some simulations.

3.2 Monetary Policy Under CBDC Viewed Through McCallum's Rule

Speculation about the impact of introducing retail CBDC is complicated by at least two factors that directly pertain to the conduct of monetary policy. First, there is potentially a significant difference between versions of CBDC which merely replaces physical cash and coins and is intended, among other objectives, to reduce "shopping costs" by raising the convenience in completing everyday transactions. In a scenario where a Public-Private Partnership between central banks and the banking sector is the vehicle used to introduce CBDC, or central banks provide the option for households and businesses to hold accounts at the central bank but offer

[44] Owing to a relatively small number of observations (18 cross-sections for annual data for the 1998-2018 sample) the residual ADF-test is, for example, -1.48 (p-value 0.16) for equation (1) and 1.35 (.09) for equation (2) when ATMs and the fraction of the poorest 20% are the institutional change proxies. Other variants (not shown) yield similar results.

no return or other services that might emerge from the availability of CBDC, the focus remains on the liabilities of the central bank. The shift in emphasis to the balance sheet of the central bank becomes even more important when CBDC are introduced as a less passive vehicle to influence the transmission of monetary policy. Beyond the foregoing implications it is worth noting that, as far as money supply injections are concerned, the unit costs to financial institutions will differ. This is outside the scope of this paper.[45]

A second problem is that, unlike other institutional developments (e.g., as in the impact of introducing a central bank; see Bordo and Siklos, 2016), we have no cases where a "treatment" (i.e., a CBDC in place) is widely available. Instead, we must imagine how a central bank's balance sheet might evolve once a CBDC is introduced. A plausible argument can be made that CBDC may have an impact likened to the fallout from previous eras of financial innovations. Resort to outside money, as well as the convenience and return from inside money, was influenced beginning in the 1970s and 1980s, at least in advanced economies, by the introduction of automatic teller machines (ATMs), and the emergence of online banking and shopping. In addition, in some countries more than in others (e.g., the United States), the spread of money market funds was given impetus by changes to post-Depression era financial regulations, known as regulation Q, that were eventually changed. However, it is quite possible that existing regulations, or the failure to adapt to a changing financial landscape, a fairly reliable interpretation of financial history, may also generate changes in finance that have yet to be contemplated. The combined impact of developments referred to above would show up at least in part in a shift away from some types of deposits in banking institutions. Indeed, if we estimate the non-cyclical variation in deposits over time based on an M3 definition of the money supply (not shown), it appears that the decades from the 1970s to the 1990s faithfully reflects the impact of technological developments in the financial industry.[46] In constructing a simulation of monetary policy under a CBDC regime this period will serve as a benchmark.

[45] Perhaps surprisingly, unit costs of financial services in a few advanced economies appear not to have declined over time in spite, or perhaps because, of the phenomenon noted by Solow in the introduction. Philippon (2019) finds that unit costs have varied considerably over time in the US but are no longer in the 2000s than in many earlier decades. Bazot (2018) generally concurs for data since the 1950s from the US, Germany, France, and the UK.

[46] The precise dates will, of course, vary but for the countries where we have long-term data the following periods (years in parenthesis) appear to capture the impact of the innovations mentioned previously. Australia (1974-1992); Canada (1974-1994), Switzerland (1962-1998), United Kingdom (1973-2011), Japan (1972-2002), Norway) (1977-1996), Sweden (1979-1993), and United States (1974-1993).

The shift in emphasis to the balance sheet of the central bank is problematic for the usual approach of assuming that the central bank can influence economic outcomes via its influence on short-term interest rates.[47] Standard New Keynesian models, even ones that recognise the existence of financial frictions, nevertheless continue to incorporate some version of the eponymous Taylor rule. However, in a world with CBDC, arguably a more appropriate policy rule is the McCallum policy rule (McCallum 1988, 1993, 2003) since it is a money growth rate rule. It also has the virtue that it is compatible with a policy regime that keeps inflation stable (e.g., see Kozicki and Tinsley 2009) or permits the price level to drift as in a price level targeting regime. McCallum money growth rule need not be in conflict with the Taylor rule (e.g., see Bordo and Siklos 2016, pp. 77-78). Furthermore, as Piazzesi et. al. (2019) demonstrate without explicitly referring to McCallum's rule, a suitably modified New Keynesian model can accommodate CBDC such that it is sensitive to money growth and changes in velocity.
There are other advantages of the rule not least of which is that, as McCallum (1988, p. 173) points out, it is "…designed to be insensitive to regulatory changes and technical innovations in the payments and financial industries."

A few additional motivations can also be highlighted to justify a money growth rule as a vehicle for incorporating a role for CBDC. Not in any particular order of importance they are: (i) Unlike the Taylor rule, the McCallum rule is not constrained by the ZLB or the ELB. Given inflation and economic activity, not to mention the negative impact of the pandemic on potential output, the ELB is a more likely occurrence than in the past; (ii) the Taylor rule assumes that only a policy interest rate dictates the stance of monetary policy. This is no longer true since the GFC as UMP have dominated the conduct of monetary policy. Indeed, post-COVID, the central bank's balance sheet is likely the main focus of monetary policy analysis. The possibility that CBDC is designed in such a way as to shift business away from commercial banks implies that central bank liabilities[48], especially the money supply, takes on a larger role. Put another way, a focus on

[47] There are also other challenges including the "short-rate disconnect" wherein the rest of the term structure is also relevant for intertemporal decisions so that links between short-term and long-term financial assets requires that an allowance be made for the fact that financial assets are not all equally safe.
[48] Or liabilities in "payment interface provider" institutions that may have a shadow element depending on how they are regulated. See, for example, Bank of Canada's decision in August 2020 to bring one such provider under the regulatory umbrella.

the central bank balance sheet is warranted and the McCallum rule is well suited for this purpose; (iii) the combination of "lower for longer" interest rates, together with population ageing, implies a possible shift in preference towards safe assets like CBDC. This too, depending on governance questions (outside the scope of our paper), shows up on the liability side of the central bank's balance sheet. Once again, the McCallum rule is better suited to capturing the influence of these developments than a conventional Taylor rule; (iv) the McCallum rule is expressed in terms of nominal GDP growth. Post-COVID reviews of monetary policy strategies may well find in favour of some form of nominal GDP targeting though the rule can very well also accommodate some form of inflation targeting.[49] Again, this makes McCallum fit for purpose; (v) some forms of CBDC represent a true expression of financial innovations. As the long-run empirical analysis reminds us this is critically reflected in the secular behaviour of velocity. The McCallum rule is directly influenced by velocity and, in a post-COVID and CBDC world, also makes it a suitable to consider the McCallum rule.

More formally the McCallum rule consists of equation (3) below and is akin to Taylor's celebrated rule because it represents a relationship between a policy instrument and the variables that enter a central bank's loss function. This is followed by two estimable forms of the money growth rule (i.e., equations (4) and (5)). Equations (6) and (7) below are added as reminders that the McCallum rule is compatible with a policy regime that keeps inflation stable while equation (5) relates nominal and real GDP growth via Okun's law (e.g., Ball et. al., 2013).

$$\Delta m_t = \Delta x^* - \Delta \tilde{v}_t + \theta(\Delta x^* - \Delta x_{t-1}), \theta = 0.5 \quad (3)$$

$$\Delta m_t = \beta_0 + \beta_1(\Delta x^* - \Delta x_{t-1}) + \boldsymbol{\beta_2 \Omega}_t + u_t \quad (4)$$

$$\Delta m_t = \beta_0 + \gamma \Delta \tilde{v}_t + \beta_1(\Delta x^* - \Delta x_{t-1}) + \boldsymbol{\beta_2 \Omega}_t + u_t \quad (5)$$

$$\bar{\pi}_t = \Delta \bar{m}_t - \Delta \bar{y}_t + \Delta \bar{v}_t \quad (6)$$

$$\Delta x_t = \Delta \pi_{t+1} + \lambda \Delta y_{t+1} \quad (7)$$

Equation (3) is a version of the McCallum rule (see Burdekin and Siklos, 2008), slightly modified from McCallum (1988), where $\Delta m_t, \Delta x^*, \Delta x_t, \Delta \tilde{v}_t$, respectively, are the observed growth rate of base money or a broad monetary aggregate (e.g., M0 or M3), the notional nominal

[49] Since nominal GDP growth is the sum of real growth and inflation policy makers have the option of setting a goal for inflation alone with the "residual" as real economic growth.

GDP growth objective, observed nominal GDP growth, and the average rate of change in the equilibrium level of velocity. Equations (4) and (5) are regression equivalent versions of (3). In both equations $\mathbf{\Omega_t}$ is a vector of other potential determinants of the policy rule. The difference between equations (4) and (5) is that, in equation (4), the assumption is that $\beta_0 = \Delta x^* - \Delta v_t$ while in equation (5) Δx^* is treated as a constant. This is akin to the question whether the constant term in the Taylor rule (the equilibrium or natural real interest rate) is a constant or not and is a testable hypothesis.

How is Δx^* estimated? One can take a "long-run" average of observed nominal GDP growth, or estimate the average low frequency variation in nominal GDP growth. Other methods are, of course, also available. Usually, simpler works best, as McCallum also found. After some experimentation we set $\Delta x^* = 4\%$.[50] This is a relatively conservative estimate and seems appropriate especially for advanced economies over the past two decades of low average inflation and real economic growth. Clearly, it is straightforward to consider other estimates for Δx^* but alternative estimates are not shown to conserve space.

Although the remaining variables in McCallum rule are observed some choices need to be made when implementing equations (3) through (5). For money growth we rely on the narrow and broad money aggregates from the Jordà-Schularick-Taylor database (http://www.macrohistory.net/data/). We label the narrow monetary aggregate M0 and the broad money supply measure is referred to as M3. In the case of the average rate of change in the equilibrium level of velocity we can readily obtain estimates from the estimated cointegrating relationships discussed above.[51]

To conserve space, we focus on the results for M0, the narrow definition of money as CBDC is likely, at least at first, to have its greatest impact on holdings of currency and demand deposits. Results for M3 closely mirror ones discussed below. Figures 8 through 10 and Table 2 display

[50] We relegate to the *appendix* a plot that illustrates the range of estimates contemplated for the nominal GDP growth objective. The 4% value chosen seems to work well with the economies considered previously for which we have long-run data.

[51] These are obtained from Figure 7. To facilitate interpretation, the values used in equations (3) through (5) are smoothed via application of the Christiano-Fitzgerald symmetric filter (3 lags, the smoothed portion represent cycles longer than 8 years). Conclusions are unaffected when the raw data shown in Figure 7 are used.

the results. Figure 8 shows observed and simulated M0 growth for the eight economies where we have long-run data. We focus on the post 1950 period since this is the era of rising financial sophistication (also see Bordo et. al., 1996). Recall that changes in equilibrium (log) levels of velocity are assumed to mimic their behaviour when, based on the historical evidence, financial innovations had their greatest impact.

Figure 8 suggests that, even with financial innovations, the gap between observed and simulated money growth explains inflation movements quite well. Hence, when observed money growth exceeds simulated values inflation rises and vice-versa. This kind of relationship is especially noticeable during the high inflation rates of the 1970s. When the gap shrinks beginning sometime in the 1990s until the end of the sample, as it does in all the countries shown, inflation declines.

Since Figure 8 is based on McCallum's original rule one might ask whether other factors ought to be controlled for and, indeed, whether the responsiveness of money growth to the deviation of notional nominal GDP growth from lagged GDP growth is 0.5 (in absolute value). Table 2 provides some estimates based on equation (5). θ is not statistically different from 0.5 for Australia, Canada, the UK, Japan, and Norway and is considerably smaller in Sweden and the US but much larger in Japan. Moreover, we can reject the unit impact of a change in velocity on money growth in all eight countries. However, in the cases of Switzerland, the UK, and Norway, velocity is not statistically significant. Overall, however, equation (5) is preferred over equation (4) to model money growth. Interest rate spreads, periods of deflation (i.e., when CPI inflation is negative) and a dummy for World Wars I and II are also frequently statistically significant.

It is unclear which version of the McCallum rule is best suited to describe money growth in a period of financial innovation. The reason is that the form in which CBDC are introduced, that is, whether there is an interest rate or other element or not beyond simply representing a digital equivalent to cash, remains to be determined. In its most basic form, the composition, if not the size, of narrow monetary aggregates will be impacted; in broader variants of CBDC discussed above, broader money aggregates will also be impacted. Figure 9 plots observed M0 growth against a range of simulated estimates based on varieties of estimates of equations (3) to (5).

Nevertheless, it is clear that under McCallum rule, and conditional on a hypothetical view of the behaviour of velocity under conditions of financial innovation, in most cases the range of simulated estimates encompass observed money growth. Only in the case of the UK is observed M0 growth comparable to the smallest simulated growth estimates. In addition, the rule provides, partly by construction, less volatile money growth than what has actually been observed.

Finally, as noted earlier, a concern in deploying CBDC is the potential impact on financial stability, as discussed in section 2(b) above, especially if central banks take a more active part in providing access to the public. Even if a more indirect strategy for introducing CBDC is envisaged (e.g., by relying on financial institutions to deploy and support CBDC) there is the potential to impact financial stability. Accordingly, we consider estimates in Table 2 and ask whether there is evidence of GARCH-like effects in McCallum's rule. Not only are these models widely used but they convey insights about the conditional volatility which tends to swing between periods of calm and episodes when the risks to financial stability rise.

We estimated EGARCH versions of equation (5) to capture the conditional volatility of money growth under a CBDC regime. Figure 10 plots the estimated conditional variances for the US (estimates for other countries are available on request). Model estimates are provided in the appendix. It is interesting to note that the spikes in conditional volatility occur at important moments in US history. They are: the founding of the Fed (1913), the deflationary and boom periods of 1919 and 1922, the recession of 1938, the tech bubble of 2000, and, by far the largest spike is obtained during the GFC of 2009. Hence, even if inflation control does not appear especially problematic via McCallum's rule, this need not prevent episodes associated with periods of financial stress or crisis from emerging even if CBDC are introduced.[52]

4. Conclusions

Interest in developing and, eventually, introducing a central bank digital currency has mushroomed recently. The ongoing pandemic has further incentivized central bankers and policy

[52] However, the proposal by Coronado and Potter (2020) to create a form of digital payment fully backed by reserves at the central bank may provide a means to prevent the estimated spikes shown in Figure 10.

makers more generally to consider digital alternatives to cash. Publicity over possible disruptions to the conduct of monetary policy from the proliferation of varieties of cryptocurrencies has also contributed to sparking more discussion.

A considerable number of challenges face central banks as they consider introducing CBDC. There are legal, technical and political economy related issues that need to be addressed. In addition, economic theory has yet to catch up to the potential micro and macroeconomic impact of CBDC though several lines of enquiry are being pursued. After an overview of the salient issues, including a few that the rapidly growing literature has not adequately considered, we suggest that history can be informative on the effects of CBDC since its aim is to impact the speed and frequency of cash-like transactions. To be sure, whether central banks allow households to directly access their balance sheet represents an important consideration.

Periods of rapid financial innovations and growing sophistication are nothing new. CBDC require a focus on the liabilities of central banks. Hence, it is appropriate to revisit how money demand and its counterpart, velocity of circulation, may be potentially impacted by technological changes in payments systems. We first show that a stable velocity function continues to require explicit recognition of institutional change. CBDC simply represents the latest vintage in a series of improvements in financial technology. Next, drawing on a period of changes in financial technology during the 1970s to the 1990s, which may offer clues about the potential impact of introducing CBDC, we revive McCallum's monetary policy rule. The rule was pushed aside by the Taylor rule better suited in a world where central banks conducted policy via interest rate changes but is well suited to a situation where the central bank is also worried about the constraints in easing monetary policy when faced with an effective lower bound for interest rates. We use McCallum's rule to illustrate that growing financial sophistication, of which CBDC is the latest manifestation, need not lead to a loss of inflation control. In addition, our findings are largely insensitive to how "money" is defined in our estimates. While this result may well change if a larger variety of definitions are used, they suggest that a suitable design for CBDC that eliminate large denominations from circulation will not hamper inflation control. We are not, however, able to take a stand on the implications of eliminating notes and coins altogether. Overall, our evidence draws from a long historical time series from eight countries although we also present some evidence using data from several emerging market economies.

What are the policy implications? First, whether central banks allow households direct access to its balance sheet will be critical. Indeed, if it is true that the unit costs of financial services have not declined over time, then pressure from the direct involvement of central banks via CBDC might lead to future reductions. However, the technical and political economy related issues that must be overcome make this option highly unlikely at present. Second, history suggests that even if inflation control is not impaired by the introduction of CBDC, digital equivalents to money likely cannot deal with all sources of financial instability. Of course, considerable caution is in order since our results are based on simulations. Real world events may well produce different outcomes. Third, though this aspect was downplayed by our analysis, it is also likely that CBDC will play a role in the relative holdings of major currencies, notably the US dollar. One reason to be cautious is because of the formidable coordination problems (again technical and political economy in nature) that stem from using CBDC as a means not only to facilitate cross-border payments but to encourage the creation of a wider portfolio of assets denominated in different currencies. Nevertheless, this element of the potential economic impact of CBDC may well prompt policy makers to revive a question that has been largely ignored for over two decades, namely the importance of currency substitution (e.g., see ECB, 2020). We are currently pursuing this extension.

Finally, even the narrow form of CBDC risks increasing the institutional and policy challenges on central banks. Arguably, central banks have yet to fully digest how far they can go in fulfilling a role in managing financial system stability. CBDC can mitigate future bouts of instability but cannot overcome all forms of financial stress. Moreover, if CBDC continues to blur the distinction between fiscal and monetary policies, the additional responsibilities may not be welcomed. Therefore, the potential remains for CBDC to be the proverbial “wolf in sheep’s clothing”.

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Table 1 Panel and Individual Cross-Section Cointegration Tests: 1870-2016

A. Conventional Velocity Function (equation (1))		
Panel: CAN, NOR, SWE, GBR, USA		
No. cointegrating vectors	Trace (p-value)	Maximal eigenvalue
r=0	*25.51 (.01)*	*33.74 (.002)*
r=1	3.52 (.97)	3.51 (.97)
r=2	7.51 (.68)	7.51 (.67)
Individual Cross-Sections		
r=0		
CAN	*33.16 (.02)*	*24.02 (.02)*
NOR	22.83 (.25)	16.66 (.19)
SWE	20.97 (.36)	17.39 (.15)
GBR	23.42 (.23)	19.17 (.09)
USA	*36.60 (.01)*	*32.28 (.00)*
r=1		
CAN	9.14 (.35)	8.89 (.30)
NOR	6.17 (.68)	4.12 (.85)
SWE	3.58 (.93)	3.58 (.90)
GBR	4.25 (.88)	4.02 (.86)
USA	4.32 (.88)	3.63 (.90)
r=2		
CAN	0.25 (.62)	0.25 (.62)
NOR	2.05 (.15)	2.05 (.15)
SWE	0.001 (.97)	0.001 (.97)
GBR	0.23 (.63)	0.23 (.63)
USA	0.69 (.41)	0.69 (.41)

Note: based on the VAR (Johansen – Fisher) test with 2 lags. Number of observations per cross-section=147. No breaks or exogenous variables added. Rejections of the null of *r* cointegrating vectors (less than or equal to *r* for the trace test; maximum of *r* vectors for the maximal eigenvalue test) are in italics, using a 5% threshold. Same notes apply to part B of the table shown below. Panel estimates include cross-section fixed effects.

B. Extended Velocity Function (equation (2))		
Panel: CAN, NOR, SWE, GBR, USA		
No. cointegrating vectors	Trace (p-value)	Maximal eigenvalue
r=0	*129.60 (.00)*	*103.90 (.00)*
r=1	*53.81 (.00)*	*47.55 (.00)*
r=2	*18.15 (.05)*	15.19 (.13)
r=3	8.01 (.63)	5.10 (.88)
r=4	8.56 (.57)	6.28 (.79)
r=5	14.06 (.17)	14.06 (.17)
Individual Cross-Sections		
r=0		
CAN	*125.84 (.00)*	*66.43 (.00)*
NOR	*113.24 (.002)*	*38.03 (.08)*
SWE	*217.92 (.00)*	*91.50 (.00)*
GBR	*134.34 (.00)*	*71.76 (.00)*
USA	*124.20 (.00)*	*58.29 (.00)*
r=1		
CAN	59.40 (.25)	22.16 (.60)
NOR	*75.22 (.02)*	30.25 (.13)
SWE	*126.42 (.00)*	*70.95 (.00)*
GBR	62.58 (.16)	30.74 (.11)
USA	65.91 (.10)	*36.29 (.03)*
r=2		
CAN	37.25 (.34)	18.50 (.45)
NOR	44.98 (.09)	21.38 (.25)
SWE	*55.47 (.01)*	*32.38 (.01)*
GBR	31.83 (.62)	16.84 (.59)
USA	29.63 (.74)	16.08 (.66)
r=3		
CAN	18.74 (.51)	12.25 (.52)
NOR	23.60 (.22)	9.90 (.75)
SWE	23.09 (.24)	15.39 (.26)
GBR	14.99 (.78)	9.50 (.79)
USA	13.54 (.87)	7.00 (.95)
r=4		
CAN	6.50 (.64)	5.54 (.67)
NOR	13.71 (.09)	8.97 (.29)
SWE	7.70 (.50)	7.46 (.44)
GBR	5.49 (.95)	5.21 (.71)
USA	6.25 (.63)	5.19 (.72)
r=5		
CAN	0.95 (.33)	0.95 (.33)
NOR	*4.73 (.03)*	*4.73 (.03)*

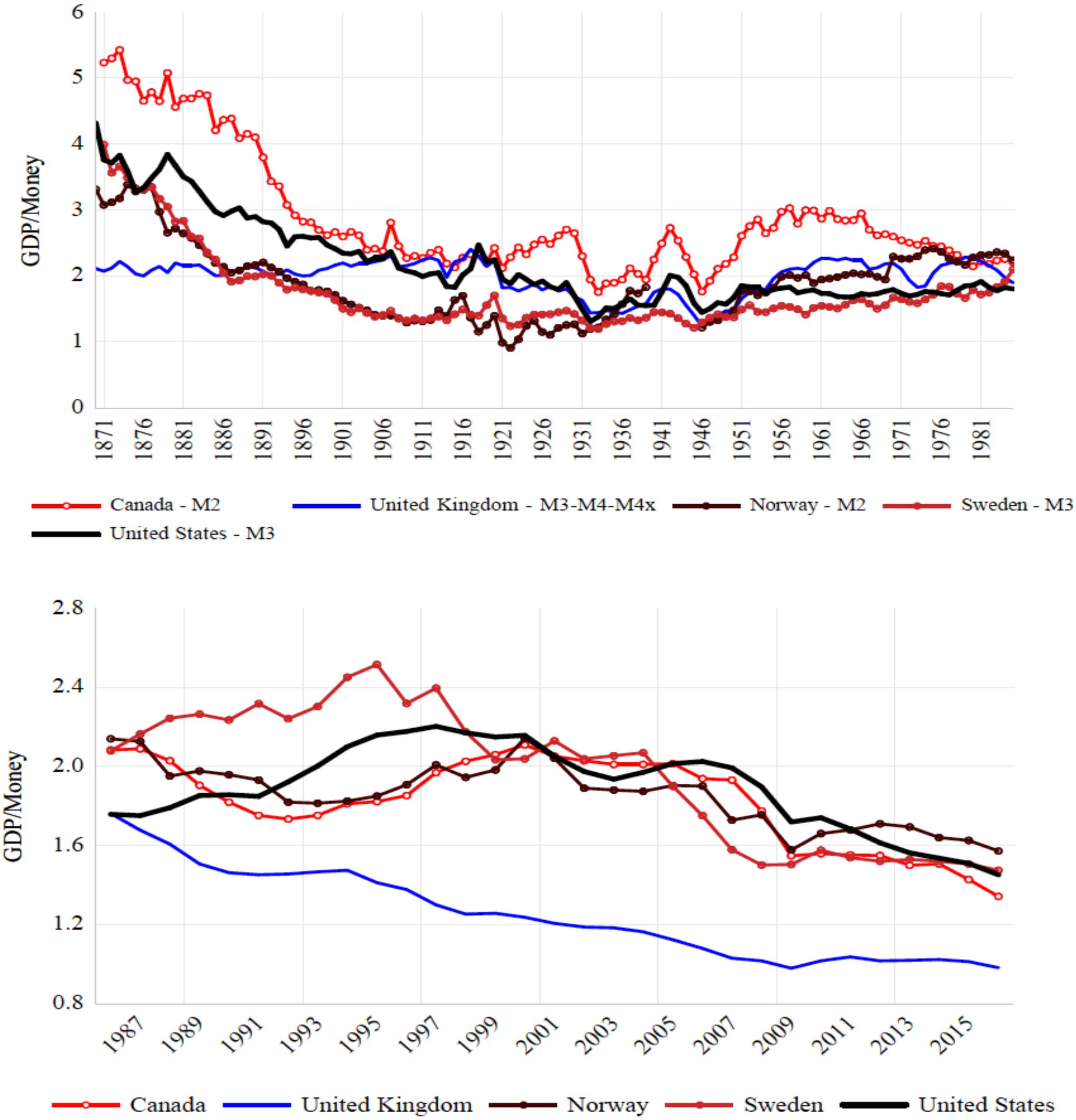
SWE	0.24 (.62)	0.24 (.62)
GBR	0.28 (.60)	0.28 (.60)
USA	1.36 (.24)	1.36 (0.24)

Table 2 McCallum Rule Estimates for Years of Financial Innovation to Mimic CBDC Effect: M0 Growth

Variable	AUS	CAN	CHE	GBR	JPN	NOR	SWE	USA
Constant	5.21* (0.92)	5.06* (1.23)	3.88 (1.12)	3.31* (0.43)	7.18* (1.55)	4.05* (1.16)	4.67* (0.69)	4.92* (0.86)
$\widetilde{\Delta \mathrm{v}}_t$	-0.60* (0.18)	-0.47@ (0.20)	-1.01 (0.15)	-0.07 (0.09)	-0.52@ (0.24)	-0.26 (0.18)	-0.38* (0.15)	-0.63* (0.15)
$\Delta x^* - \Delta x_{t-1}$	-0.32* (0.12)	-0.43* (0.15)	-1.01 (0.15)	-0.40* (0.06)	-0.56* (0.07)	-0.34* (0.12)	-0.10 (0.09)	-0.26@ (0.11)
$r_{Lt} - r_{St}$	0.15 (0.63)	0.84 (0.57)	-0.28* (0.14)	0.38+ (0.20)	0.71+ (0.42)	0.61 (0.84)	0.97@ (0.43)	0.54 (0.51)
Deflation	-1.96 (2.07)	-8.06+ (4.10)	0.45 (0.39)	-2.18@ (0.93)	1.78 (2.39)	-2.87 (2.45)	-4.10* (1.37)	-1.45 (2.36)
World Wars	6.83* (2.43)	7.20* (2.46)	-3.19 (1.95)	10.40* (1.22)	16.33* (3.76)	17.64* (3.57)	13.23* (1.90)	6.93* (2.49)
Years of Innovation	1974-1992	1974-1996	1962-1998	1973-2011	1972-2002	1977-1996	1979-1993	1974-1993
Adj. R^2	0.23	0.30	0.31	0.68	0.58	0.34	0.56	0.22
F	8.23*	7.62*	12.00*	51.05*	25.55*	15.44*	21.16*	8.24*
Observations								

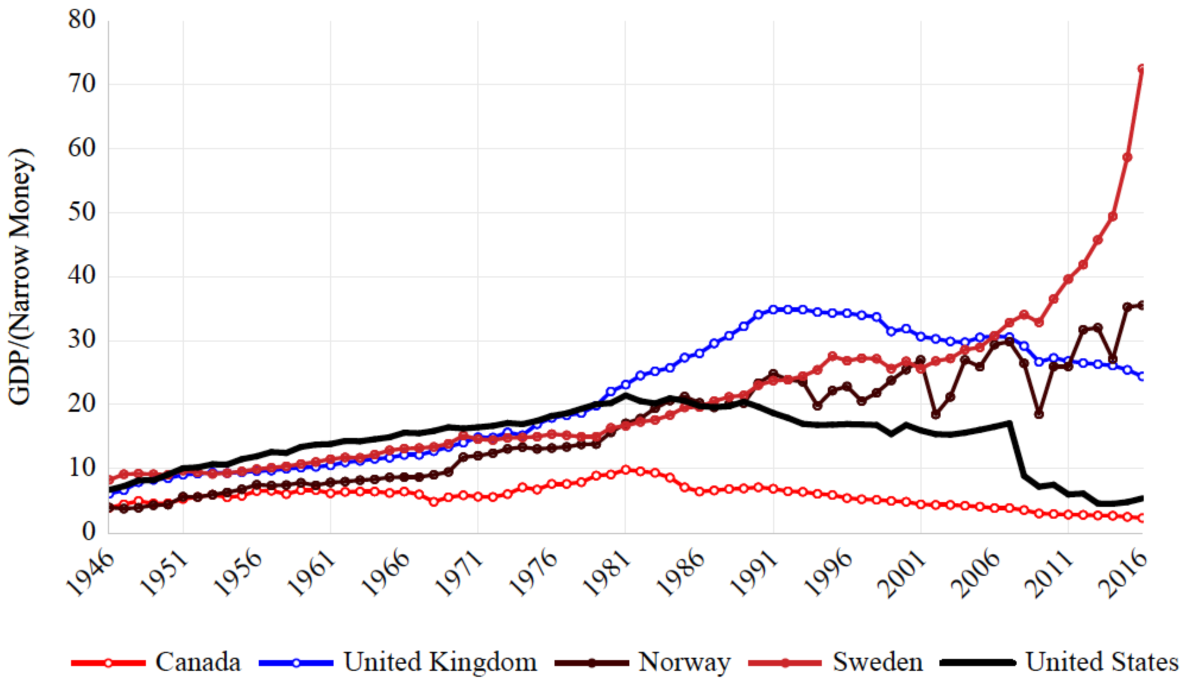
Note: Estimates of equation (5). Standard errors in parenthesis. * means significant at the 1% level; @ at the 5% level; + at the 10% level. Estimated via least squares. Countries: AUS (Australia); CAN (Canada); CHE (Switzerland); GBR (United Kingdom); JPN (Japan); NOR (Norway); SWE (Sweden); USA (United States).

Figure 1 Velocity of Circulation in Five Countries: 1870-2016



Note: Calculated from the Jordà-Schularik-Taylor database (http://www.macrohistory.net/data/). Money is measured as shown in the legend of the top figure. The bottom figure is the same data but from 1987. Data are annual.

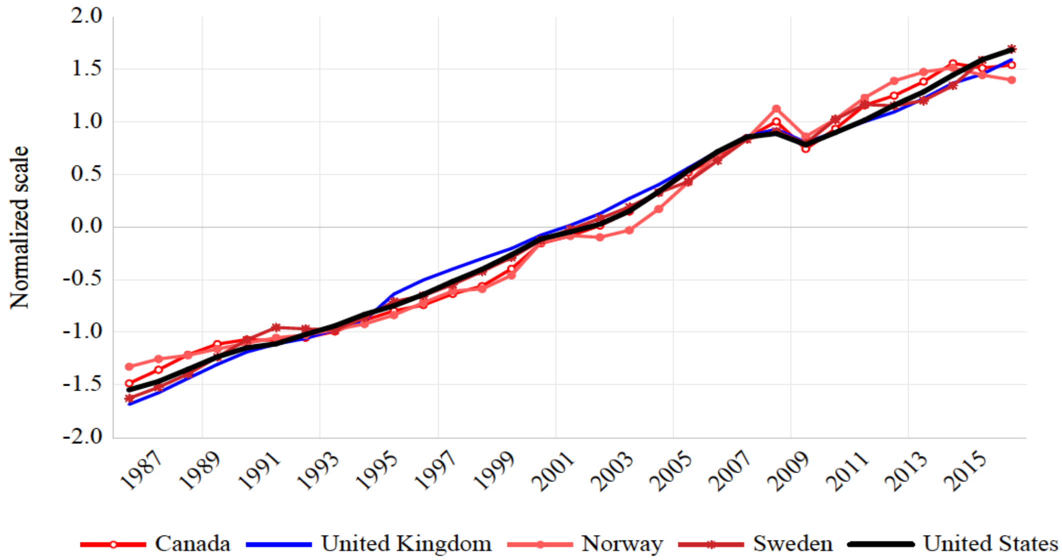
Figure 2 Velocity of Circulation Since the late 1980s in Five Countries



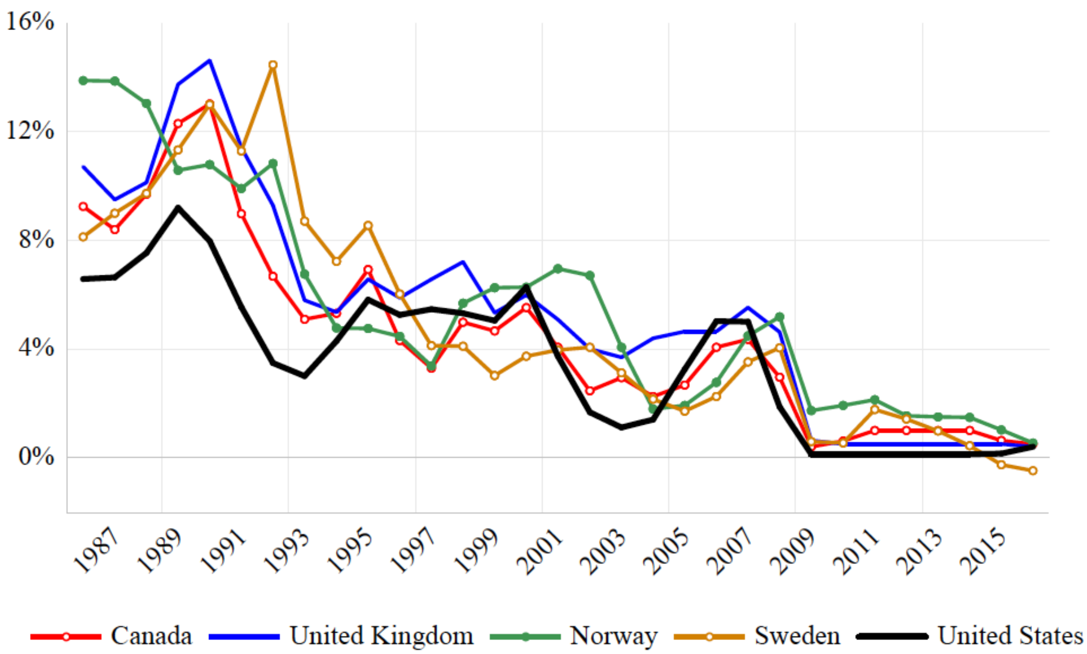
Note: Source same as in Figure 1. Narrow money is currency notes and coins in circulation plus demand deposits. Data are annual.

Figure 3 Real Per Capita GDP and Policy Rates in Five Countries: 1987-2016

(a) Real per capita GDP

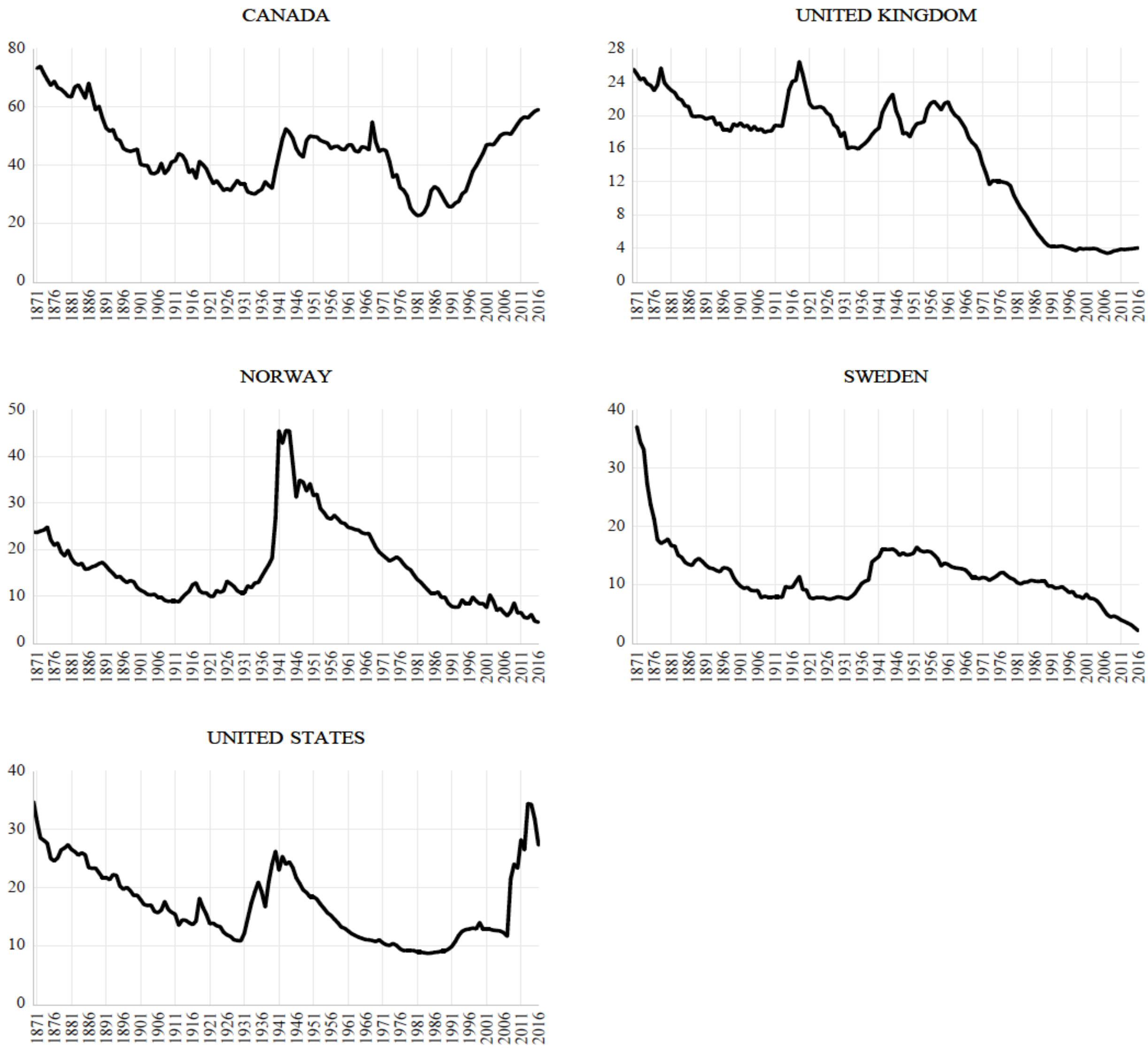


(b) Policy interest rates



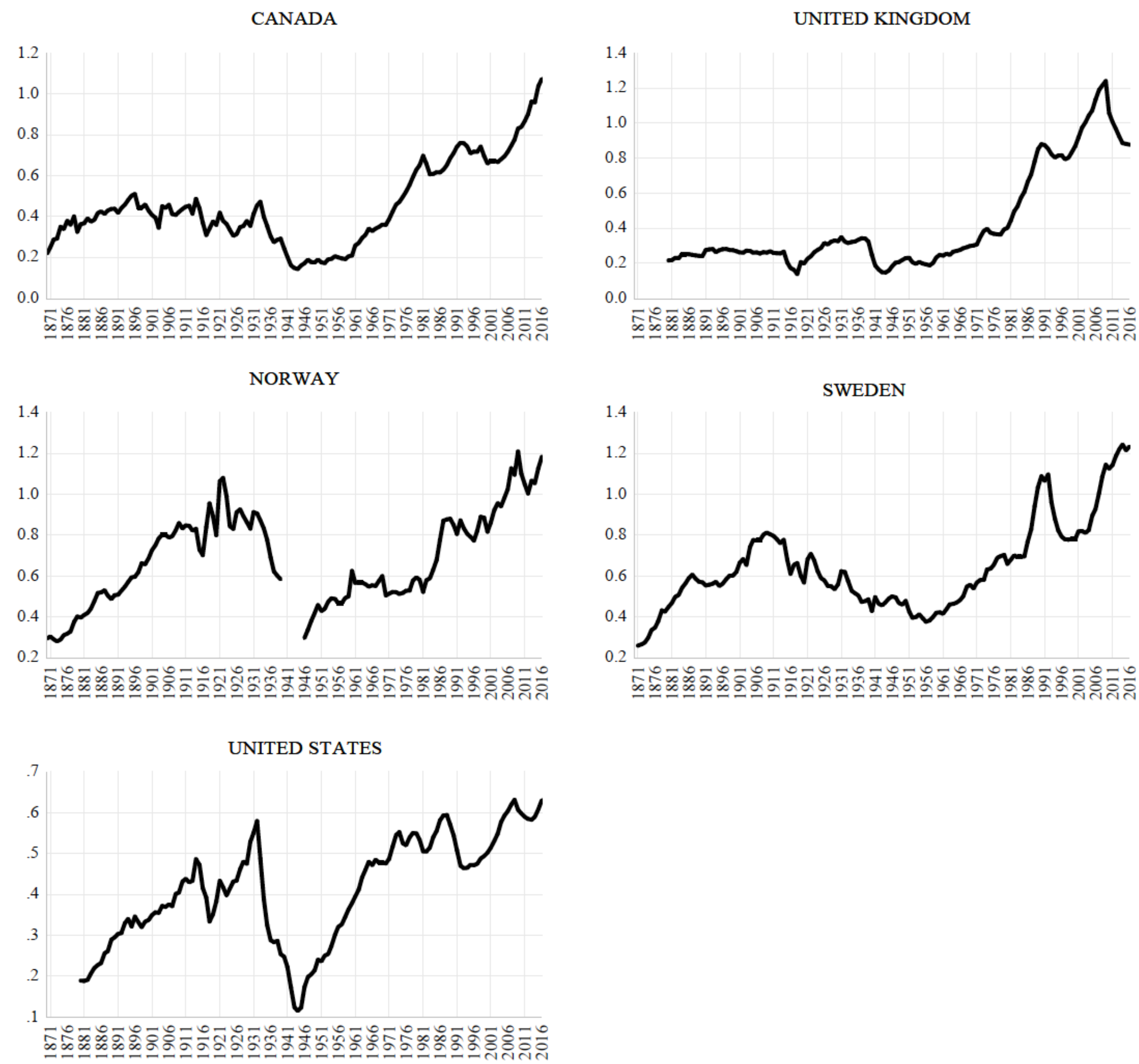
Note: Data for the top figure obtained from the same source as in Figure 1. Data used as provided. Other than the normalization no other calculations made. Bottom figure is from BIS Statistics (https://www.bis.org/statistics/cbpol.htm?m=6%7C382%7C679). Data are annual. BIS data originally monthly but simple arithmetic average used to create annual data.

Figure 4 Currency to Money Ratio in Five Countries: 1870-2016



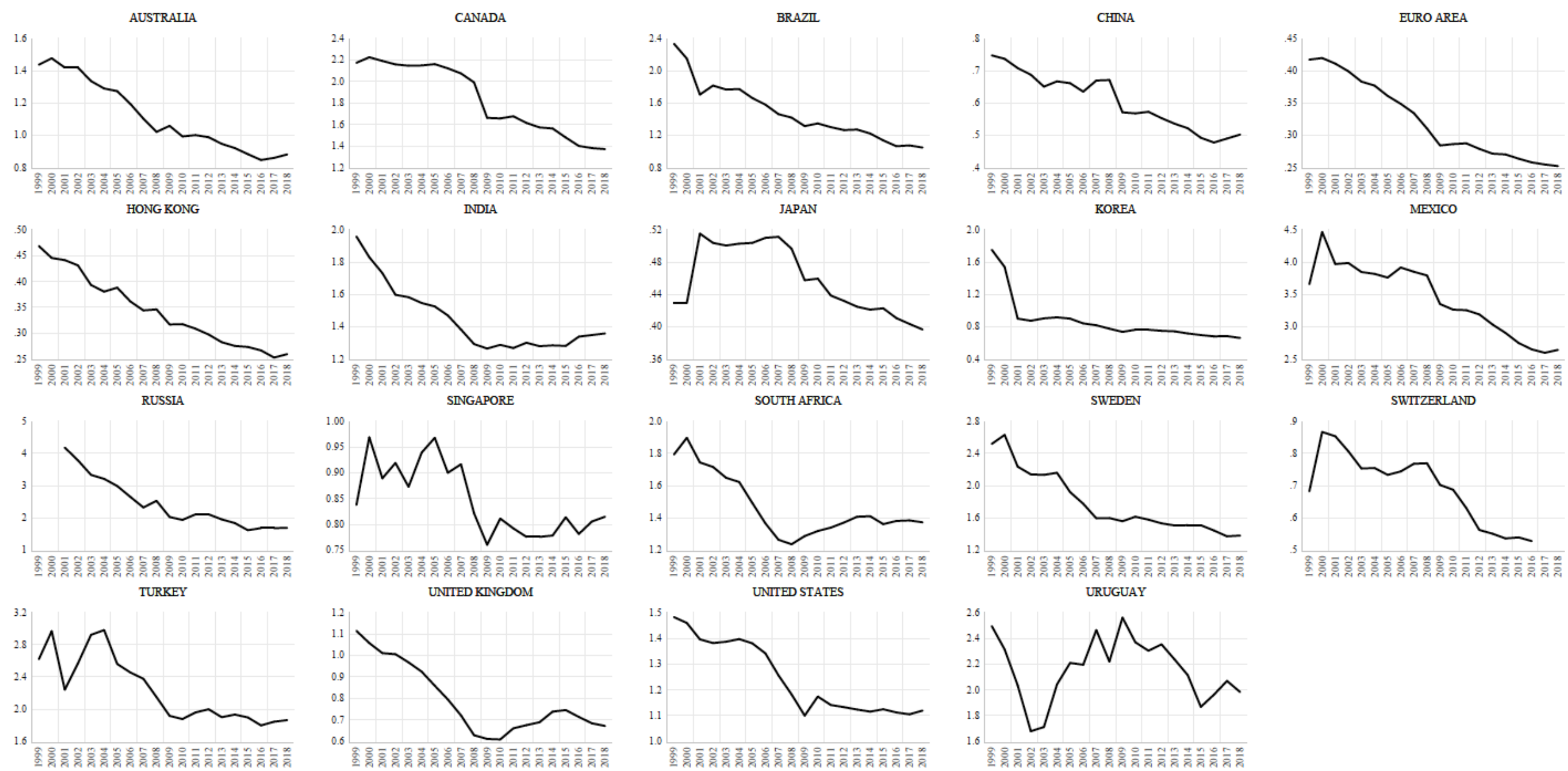
Note: in percent. Data from the same source as in Figure 1. “Currency” is narrow money (see Figure 4), “money” is broad money (see Figure 1). Data are annual.

Figure 5 A Proxy for Financial Innovation in Five Countries: 1870-2016



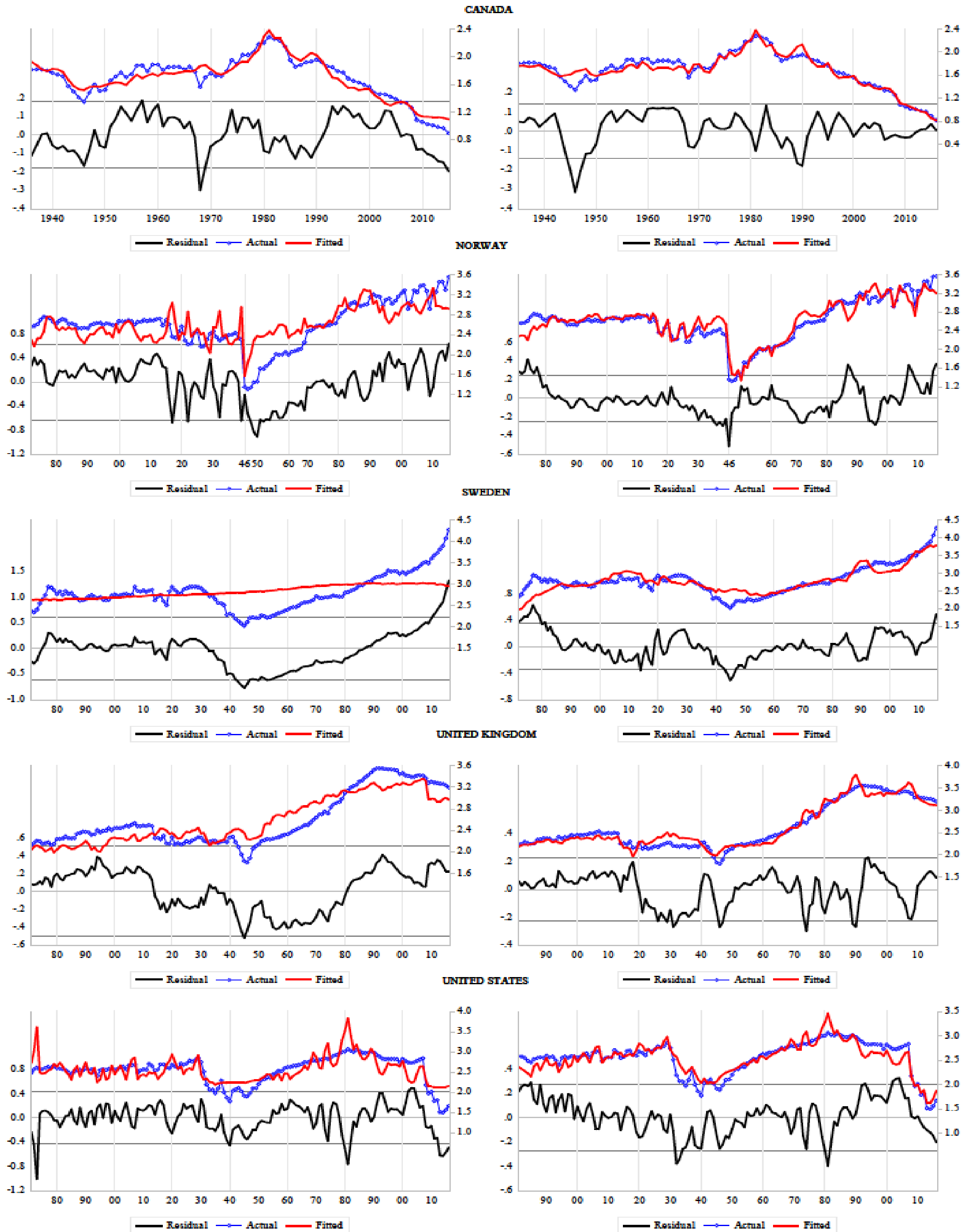
Note: Data from the same source as in Figure 1. Gap for Norway due to World War II is filled via interpolation (Catmull-Roll Spline) in the estimated specifications. The ratio shown is Total Loans to non-bank private sector over GDP. Data are annual.

Figure 6 Velocity of Circulation in 19 Economies: 1999-2018



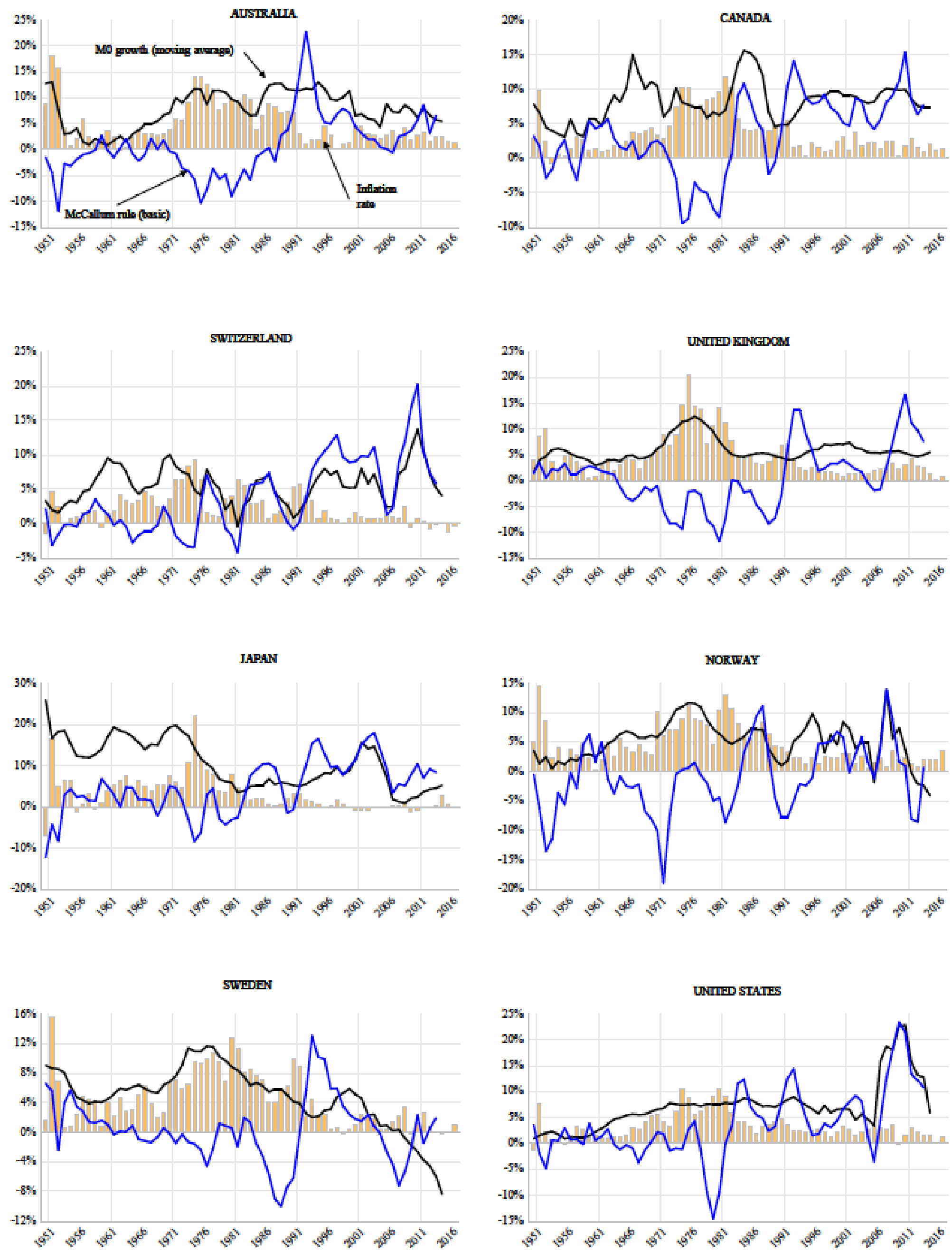
Note: Data for GDP divided by estimate of broad money (IMF definition) obtained from World Bank Development Indicators (https://databank.worldbank.org/source/world-development-indicators). Data are annual.

Figure 7 Cointegrating Equations, Error Correction, and Velocity of Circulation in Five Countries: 1870-2016



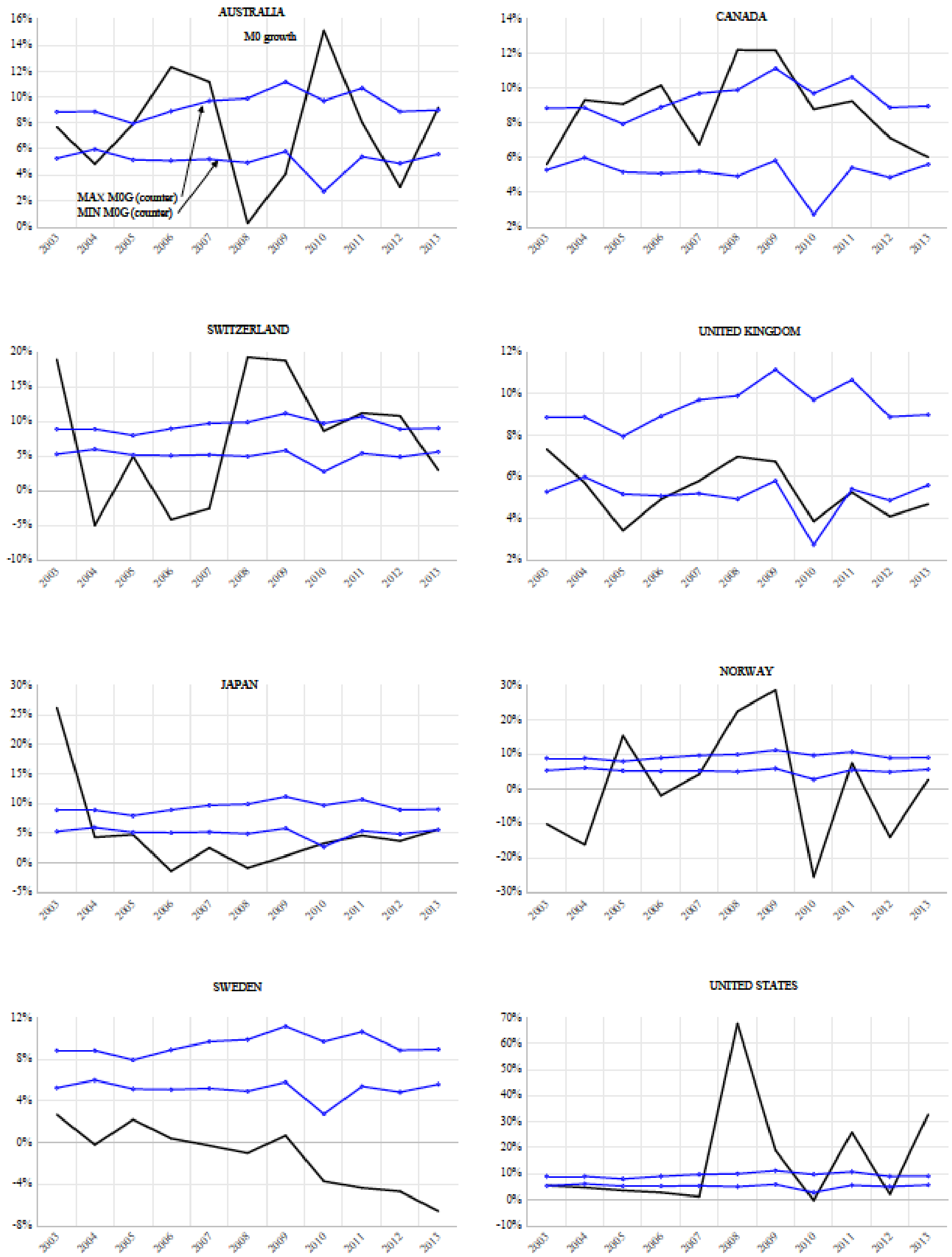
Note: All cointegrating equations estimated via fully modified OLS. The fitted values are estimates of the cointegrating relationships for the conventional (equation (1), left hand-side column) and extended velocity models (equation (2), right hand-side column).

Figure 8 McCallum Rule for M0 Growth, Observed M0 Growth and Inflation



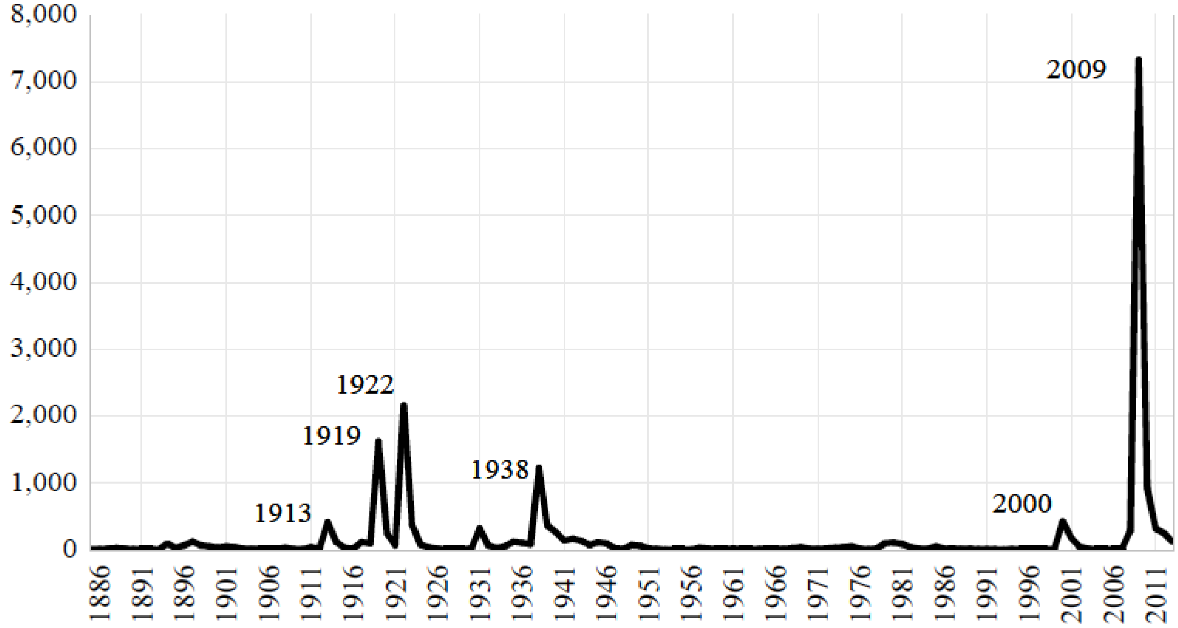
Note: McCallum rule equation (3). Inflation is CPI inflation. M0 Growth (5 year centred moving average) and CPI from same source as Figure 1. See the text for additional estimation details including some smoothing of certain series via application of the Symmetric Christiano-Fitzgerald filter.

Figure 9 Hypothetical (Counterfactual) M0 Growth Under a CBDC Regime



Note: Varieties of McCallum rules (equations (3) through (5)) estimated and maximum (MAX M0G) and minimum estimates (MIN M0G) obtained are plotted to provide a range of hypothetical values for narrow money growth under a CBDC regime. See text for estimate details.

Figure 10 Conditional Variance: McCallum Rule for USA M0 Growth



Note: Conditional variance estimates from EGARCH fitted to equation (4).