# Inflation and Welfare in the Laboratory*†

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This version: January 2021

**Abstract**

We develop an experimental framework to investigate the quantity theory of money and the effect of expected inflation on output and welfare based on the Rocheteau and Wright (2005) model of monetary exchange. We compare a laissez-faire policy with a fixed money supply and three policies with constant money growth where newly issued money is used to finance government spending, lump-sum transfers, or proportional transfers, respectively. The experimental results are largely consistent with theory. The quantity theory of money holds and higher money growth leads to higher inflation. Relative to laissez-faire, output and welfare are significantly lower with government spending, output is significantly lower with lump-sum transfers, while there are no significant real effects with proportional transfers. A substantial deviation from theory is that the detrimental effect of money growth depends on the implementation scheme and is weaker with lump-sum transfers relative to government spending.

**JEL Classification**: C92, D83, E40

**Keywords**: money, monetary policy, inflation, experimental macroeconomics

*We thank John Duffy, Ricardo Lagos, Gary Richardson, Guillaume Rocheteau, Randall Wright, Sevgi Yuksel and seminar and conference participants at U.C. Irvine, King's College London, Virginia Commonwealth University, Midwest Macro Meetings at Michigan State, SED Meetings in St. Louis, ESA World Meeting in Vancouver, Workshop on Theoretical and Experimental Macroeconomics in Ottawa, Money, Banking, and Finance Summer Workshop in Ottawa, Conference on Theory and Experiments in Monetary Economics in Arlington, Jordan-Wabash Workshop in Experimental Economics at Purdue, and the Southwest Search and Matching Conference at U.C. Irvine. We gratefully acknowledge support for this project from Bank of Canada and the Department of Economics at Indiana University. The views expressed in this paper are those of the authors. No responsibility for them should be attributed to the Bank of Canada.

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# 1 Introduction

The long run effects of monetary policy on inflation, output, and welfare are both of classical and contemporary interest in monetary economics and central banking (see e.g. Lucas 2000, Diercks 2019, Bernanke 2020).[1] On the long run effect of monetary policy on inflation, the quantity theory prediction that prices respond proportionally to changes to the money supply has received ample confirmation empirically over time and across countries (see e.g., Lucas 1980; Friedman and Schwartz 1987; Rolnick and Weber 1997).[2]

However, the literature has yet to reach a consensus on the effects of anticipated inflation. Monetary theory has suggested various channels through which expected inflation could affect the real economy. Inflation may increase or decrease welfare, depending on the chosen theoretical framework.[3] A classic view dating back to Bailey (1956) is that inflation increases the opportunity cost of holding money, thereby inducing individuals to economize on cash, which reduces economic activities and welfare. This mechanism lies more generally at the heart of cash-in-advance models such as Stockman (1981) and microfounded models such as Shi (1997) and Lagos and Wright (2005). The Great Inflation of 1965-1982 dramatized the detrimental effects of high inflation and prompted many central banks to explicitly or implicitly target a moderate inflation rate. Following the Great Recession of 2007-2009, higher inflation targets have been proposed to give monetary policies more room to fight recessions at the zero lower bound (see e.g., Eberly, Stock, and Wright 2019, Bernanke 2020). Policymakers have been mindful about the detrimental effects of inflation and so far cautious about raising the inflation target. Similarly on the empirical side, there is no robust evidence on the long-run real effects of inflation (see Ragan 1998 and references therein).

In this paper, we develop an experimental framework to study the quantity theory of money and the effects of expected inflation, implemented through anticipated changes in the money supply.[4] Our focus is on the inflation tax channel typically associated with detrimental effects of inflation on monetary exchange, output, and welfare. The experimental approach allows us to isolate the channel of interest and to study whether particular monetary policies

[1] Monetary policies in response to short-term fluctuations are also important but not the focus of the present paper.

[2] Recent evidence from the Great Recession of 2007-2008 suggests the quantity theory may not hold in times of crises. See e.g. Anderson, Bordo, and Duca (2014) and Lucas and Nicolini (2015).

[3] Diercks (2019) surveys academic papers published since the mid-1990s on the topic of optimal monetary policy, and discusses costs and benefits of inflation in different environments.

[4] Anticipated changes in the money supply are a traditional inflationary policy tool which we consider as a natural first step in studying monetary policy in the lab. We intend to study other policies such as open market operations and quantitative easing in future projects.

work as intended in an environment with internal validity.[5]

Our experimental design is based on a version of the New Monetarist model proposed by Rocheteau and Wright (2005) where money plays an explicit role by serving as a medium of exchange.[6] Precisely because of this role, inflation erodes money's purchasing power in this framework, thereby reducing output and welfare. Anticipated inflation influences real variables operating through the inflation tax. The model is microfounded, making it amenable to laboratory investigation and welfare analysis.[7] Agents trade in two centralized markets that open sequentially and have quasilinear preferences in the second market. The alternating market structure and the quasilinear preferences make the model stationary since agents solve the same problem each period and there are no transitional dynamics. This also simplifies welfare analysis because only consumption and output in the first market are relevant for welfare.[8] Monetary policies are represented by anticipated growth in the money ("token") supply with money injections occurring in the second market. As in Duffy and Ochs (1999) and Duffy and Puzzello (2014ab, 2018), subjects are instructed that tokens are intrinsically useless and cannot be redeemed for points.

As a benchmark, we keep the token supply constant in the Constant Money treatment. We then implement three different schemes for money growth – namely through government purchases, lump-sum transfers ("helicopter drops"), and proportional transfers to money holdings – and study their impact on prices, output, and welfare relative to the benchmark treatment. In the Government Spending treatment, a computerized robot is pre-programmed to purchase goods in the second market, thereby injecting tokens in the economy. In the Lump-Sum Transfers treatment, consumers receive a lump-sum transfer of tokens at the start of the second market. Finally, in the Proportional Transfers treatment, all subjects receive a transfer proportional to their token holdings at the beginning of the second market. In a stationary equilibrium, theory predicts inflation is zero in the Constant Money treatment while positive and equal to the token growth rate in all inflationary treatments. In terms of real effects, money growth implemented by government spending and lump-sum transfers

[5]If policies do not work as intended in controlled laboratory economies, there is little hope that they would be effective in field settings where different channels may be simultaneously at work.

[6]Recent work by Lagos and Zhang (2019, 2020b) shows that abstracting away from a role of money as a medium of exchange is not without loss of generality for cashless monetary models.

[7]Quantitative applications of New Monetarist models show the models are empirically relevant; see e.g. Berentsen, Menzio and Wright (2010), Lagos (2010), Aruoba, Waller, and Wright (2011), Rocheteau, Wright, and Zhang (2018), Lagos and Zhang (2020a), Bethune, Choi, and Wright (2019), among many others.

[8]The alternating centralized market structure is reminiscent of Bewley (1980) and Townsend (1980) where agents periodically alternate between the roles of buyers and sellers. The Rocheteau-Wright model with two centralized markets can be interpreted as a special case of the Bewley-Townsend model with quasilinear preferences in one market.

has detrimental effects on output and welfare relative to the Constant Money treatment. In these environments, agents respond to the tax associated with higher inflation by reducing real cash holdings, and thus consumption and production. The third policy scheme provides an additional test of the inflation tax channel since the distortionary effect of inflation is neutralized by the proportional transfer, so that output and welfare are identical to the Constant Money treatment. Specifically, in this setting, agents do not reduce consumption or production in response to inflation. This is because the proportional transfer compensates them for the inflation tax. This treatment provides additional validation for the model mechanism, as theory predicts that inflation does not have real effects. We then use the laboratory to explore the following questions: Do anticipated changes in money supply transfer to prices? If money growth generates inflation, do subjects perceive it like a tax in treatments where money injections are predicted to have real effects on output and welfare?

The results of our experiment are largely consistent with the theoretical predictions of the dynamic monetary model, though we also observe results departing from the theory. Specifically, we find evidence in support of the quantity theory of money: average inflation is close to the money growth rate in all treatments. In terms of real effects, we also find money growth and inflation reduce output and welfare in the Government Spending and Lump-Sum Transfers treatments but have no real effects under Proportional Transfers. These qualitative insights suggest that the tax channel mechanism is behind the data patterns we observe in the Government Spending and Lump-Sum treatments. We view these results are nontrivial since inflation, production, and consumption are *endogenously* determined by subjects interacting in a dynamic laboratory environment. A departure from the theory is that the detrimental effect of money growth or inflation depends on the implementation scheme, and is stronger under Government Spending than under Lump-Sum Transfers. This result can be in part attributed to the somewhat higher inflation rates observed in the Government Spending treatment, in their turn due to the automatic spending of computerized robots.

Overall, our findings suggest that the laboratory "institution" we developed can support the study of a wide range of questions in monetary economics. We view our experimental study as a complement to theoretical and empirical work on the long-run effects of expected inflation. The approach to test the channels suggested by monetary theory with field data faces unique challenges that can be alleviated with controlled laboratory methods. First, confounding factors beyond the control of the researcher may affect how perceived inflation maps into actions, e.g., concurrent economic policies, unobserved preference heterogeneity and budget constraints. Second, individuals may have different perceptions about inflation depending on personal purchasing habits, characteristics, and information sets. In the laboratory, we induce preferences directly by converting consumption to points using a particular utility function, and points are directly linked to monetary payments. Subjects trade the same set of goods and observe the same set of prices (which are shown to subjects on the computer screen where they input purchase and production decisions), making it straightforward to infer inflation from the time path of prices. We can also directly observe individual budget constraints and choices.[9]

The remainder of the paper is organized as follows. Section 2 discusses related literature. We introduce the theoretical framework in Section 3. Section 4 describes the experimental design and procedures, and Sections 5 reports the experimental results. We conclude in Section 6.

## 2 Related Literature

In this section, we focus our discussion on papers that are closely related to our study (see Duffy 2016 or Hommes 2020 for a review of papers studying macroeconomic policies in the laboratory). This paper is related to other experimental studies on money as medium of exchange. Brown (1996), Duffy and Ochs (1999, 2002), Camera, Noussair, and Tucker (2003), Berentsen, McBride, and Rocheteau (2017) analyze the role of money as a medium of exchange. Camera and Casari (2014) and Duffy and Puzzello (2014a) investigate allocations in environments with money and without money. They find evidence in support of the essentiality of money. Davis et al. (2019) consider environments where monetary exchange may or may not be supported as an equilibrium arrangement in finite-horizon economies. Jiang and Zhang (2018), Ding and Puzzello (2020), and Rietz (2019) study currency competition in dual currency search models. In these studies, either prices are exogenous or there is no money growth and hence inflation. Baeriswyl and Cornand (2018) study a general equilibrium environment without frictions and one-time monetary injections. The authors consider two types of monetary injections: credit expansion and lump-sum transfers. Theory predicts that money is neutral, regardless of the monetary injection process. However, the author finds that credit expansion distorts the allocation of resources, while lump-sum transfers do not. Duffy and Puzzello (2014b) find evidence in support of money neutrality when money

[9]More generally, while the experimental method is more widely used to address microeconomic questions, there are also several advantages in extending the method to macroeconomics and monetary policies in particular (see Duffy 2016 and Hommes 2020 for recent reviews of research in experimental macroeconomics). In the laboratory, we can test the effects of monetary policies that would be too difficult or costly (in terms of disrupting the actual economy) to implement in the field. When we observe behavior deviates from theoretical predictions, we can examine the accurately-recorded lab data to explore underlying reasons.

supply is doubled but not when it is halved.[10]

There are also experimental studies focusing more specifically on the effects of inflationary monetary policy. Marimon and Sunder (1993, 1994, 1995), Lim, Prescott, and Sunder (1994), and Bernasconi and Kirchkamp (2000) implement an overlapping generations (OLG) model to study the role of money as a store of value and effects of hyperinflation. An advantage of using the Lagos and Wright (2005) or Rocheteau and Wright (2005) model is it provides clearer welfare predictions on the effects of money growth (e.g., with OLG models, one must decide the weights attached to different generations for welfare calculations).

Deck, McCabe, and Porter (2006) study the effects of inflationary monetary policies in a finitely repeated double auction market where two types of subjects trade for the other type's goods through fiat money. They find subjects are able to coordinate on using money as a medium of exchange, but an active government played by additional subjects that make proportional injections of new money can lead to hyperinflation and trading collapses. They argue the main reason for this economic failure is not the increasing money supply, but the undermining of the market's ability to coordinate trade.

Lian and Plott (1998) implement a cash-in-advance finite horizon general equilibrium monetary economy. To circumvent backward induction arguments, money held at the end of the experiment is converted into real values, based on the final period average price. In one of their sessions, money supply is increased at a rate of 18.9% in each period of a specific segment of the horizon. Like in our experiment, increases in the money supply occur via lump-sum transfers. However, in contrast with our framework, the transfers are unanticipated, start in period four and stop after eight periods. The authors document inflation, but no real effects.

Anbarci, Dutu, and Feltovich (2015) study the effects of an inflation tax in a version of the Lagos and Wright (2005) model with price posting as in Burdett, Shi, and Wright (2001). While they find the inflation tax has detrimental effects on production and welfare, subjects in their experiment make static choices, and the inflation tax is implemented by having buyers borrow money from a bank at a specified interest rate that proxies for the inflation tax. In contrast, our experimental setting is fully dynamic where subjects can adjust their money holdings and carry over money balances over time. Prices and therefore inflation are endogenously determined and subjects' behavior indicates that inflation is indeed perceived as a tax.

[10] Their focus is on an environment with frictions, where one-time money supply changes occur via lump-sum transfers.

The closest paper to ours is Duffy and Puzzello (2018), who also use a New Monetarist model to investigate the effect of monetary policies. Their study differs from ours in terms of the main research question, experimental framework and design, and experimental results. While our study focuses on the effects of inflationary monetary policies and different ways to inject new money into the economy; Duffy and Puzzello (2018) focus on the implementation of the optimal monetary policy, namely the Friedman rule, through deflation or paying interest on money, even though they also consider an inflationary monetary policy. Further, the experimental design of the two papers differ in several key aspects. Our experimental framework is based on the competitive version of Rocheteau and Wright (2005), where trade always occurs in competitive markets and the roles of buyers and sellers are fixed. Duffy and Puzzello (2018) use the Lagos and Wright (2005) framework where agents trade in pairwise meetings and buyers make take-it-or-leave-it-offers. While subjects observe the full history of market prices in our experiment, subjects in Duffy and Puzzello (2018) do not observe inflation or prices outside of their match. We also adopt a different timing of monetary transfers (to achieve a more controlled comparison of different money growth schemes) and a higher probability of continuation.[11] In terms of results, while our findings are largely consistent with theory as inflation reduces output and welfare, Duffy and Puzzello (2018) find the opposite. Their results can be in part attributed to the additional frictions associated with the decentralized market (e.g., no inflation or deflation was observed in these markets) and to the presence of liquidity constraints that were alleviated by lump-sum transfers occurring at the end of the centralized market. We conjecture that differences in experimental designs, including the different trading mechanism, may play an important role in understanding the differences in the findings, and we leave a more exhaustive exploration of these factors for future research.[12]

[11] In Duffy and Puzzello (2018), lump-sum taxes or transfers occur before subjects enter a pairwise match, which implies that the liquidity constraint in the decentralized market could be more severe for the Friedman rule treatments relative to other treatments.

[12] We note that the policies we consider work as intended if: (i) money supply changes transfer into price changes appropriately, and (ii) subjects observe price changes and respond to them as predicted. For example, if money supply growth is positive, subjects' production and consumption choices should be such that there is inflation in the laboratory economy. Further, subjects should receive unequivocal signals regarding prices, and thus inflation. Finally, they should perceive inflation as a tax and reduce consumption and production in response to it. In the laboratory, different trading protocols may affect the price formation mechanism differently, and thus have an impact on these channels. We leave a controlled comparison of decentralized and centralized trading protocols for future research.

# 3 Theoretical Framework

Our experimental economy is based on a simple version of the competitive markets new monetarist model of Rocheteau and Wright (2005). This new monetarist model provides microfoundations for money as a medium of exchange, and the alternating market structure with quasilinear preferences renders the model easy to solve analytically, making it well suited for laboratory implementation.[13] There is a large literature that investigates the effects of inflation on output and welfare in search theoretic models; see e.g., Lagos and Wright (2005), Rocheteau and Wright (2005), Molico (2006), Aruoba, Rocheteau, and Waller (2007), Craig and Rocheteau (2008), and Chiu and Molico (2010). We choose the competitive markets version of Rocheteau and Wright (2005) so that all subjects observe the same price signals in each market. This is an important consideration since price signals are a crucial factor for the policy to work as predicted by theory. In this section, we describe the environment and use it to derive testable implications on the effects of monetary policy through different ways of implementing changes in money growth.

## 3.1 Environment

Time is discrete and continues forever. There are two types of agents, called type A and type B, each of size $N$. Each period consists of two markets, A and B, that open in sequence. In each market, there is a divisible and perishable good, called good A in market A and good B in market B. In market A (B), type A (B) agents want to consume but cannot produce, while type B (A) agents can produce but do not to consume, i.e., there are gains from trade. All agents discount between periods with a constant discount factor $\beta \in (0, 1)$. Instantaneous utilities for type A and B agents are given by:

$$\boldsymbol{U}^A = u(x_A) - x_B,$$

$$\boldsymbol{U}^B = -x_A + v_0 + x_B,$$

where we use the subscript to label the good or market, and the superscript to label the agent's type. Type A derives utility $u(x_A)$ from consuming $x_A$ units of good A, where $u'(0) > 0, u''(0) < 0$ and $u'(0) = \infty$, and incurs disutility $x_B$ from producing $x_B$ units of

[13] An important advantage of the alternating market structure and quasilinear preferences is analytic tractability since these assumptions make the distribution of money holdings degenerate. In our setting, there are no shocks so quasilinear preferences are not required for tractability. Nonetheless these preferences greatly simplify the model solution – by removing transitional dynamics – and welfare analysis – since we can focus on consumption and output in one market.

good B. For type B agents, the disutility from producing good A is $x_A$, and the utility from consuming good B is $v_0 + x_B$.[14] The first-best level of output in market A is $x_A^*$ such that $u'(x_A^*) = 1$.

Lack of commitment, no formal enforcement, and private trading histories restrict the emergence and sustainability of credit arrangements and a lack of double coincidence of wants rules out barter.[15] There is a single intrinsically useless asset, called money, that could serve as a medium of exchange. Money is divisible and storable in any amount, $m_t$. The money supply at the start of period $t$ is $M_t$, which grows at a constant gross rate $\gamma \geq 1$, i.e., $\gamma \equiv M_{t+1}/M_t$. New money is injected at the beginning of each market B in one of three ways: (1) to finance government spending, (2) to finance lump-sum transfers to type B agents (who are consumers in market B), and (3) to finance transfers proportional to money holdings at rate $\tau = \gamma - 1$.

## 3.2 Monetary Equilibrium

We focus on steady state equilibria where the real variables and the inflation rate is constant over time. As in Lagos and Wright (2005) and Rocheteau and Wright (2005), we start backwards by first characterizing agents' decision problems in market B, and then we use that to solve for their choices in market A. We then describe equilibrium allocations, prices, and welfare across different inflationary regimes.

### Market B Optimization Problems

In market B, agents trade good B and money in a competitive market where the price of good B is $p_B$. The value function of a type $i$ agent who enters market B with money holdings $m^i$ satisfies

[14] In the original setting in Lagos and Wright (2005) and Rocheteau and Wright (2005), agents have quasilinear preferences in market B: they derive concave utilities from a general good and linear utilities (disutilities) from leisure (labor). We adopt the linear preferences to simplify the environment so that subjects decide only on one object in market B. The term $v_0$ is intended to equalize payoffs between type A and type B agents in the laboratory implementation of this economy (theory predicts type B earns zero if $v_0 = 0$). Introducing this term does not affect equilibrium predictions.

[15] Here only aggregate outcomes, i.e., prices, are observable. Nonetheless, since the population is finite in the laboratory, informal enforcement schemes are theoretically possible (see Aliprantis et al. 2007 and Araujo et al. 2012). However, Duffy and Puzzello (2014a) find that laboratory outcomes in economies of 6 and 14 subjects are closer to the monetary equilibrium predictions and do not find support for the emergence of informal enforcement schemes.

$$\begin{aligned} \max_{\hat{m}^i, x_B^i} W(m^i) &= \max_{\hat{m}^i, x_B^i} \left\{ x_B^i + v^i + \beta V^i(\hat{m}^i) \right\} \\ \text{subject to } \hat{m}^i &= -p_B x_B^i + (1+\tau) m^i + T^i, \end{aligned} \tag{2}$$

where $\tau$ is the rate of proportional transfers, $v^A = 0, v^B = v_0$, $x_B^i$ is net consumption of good B,[16] $\hat{m}^i$ is the choice of money holdings in the next market A, and $T$ denotes the lump-sum transfer of money by the government, expressed in nominal terms ($T^A = 0$, and $T^B$ can be positive). That is, a type B agent, is a net consumer in market B and finances her end-of-period money holdings and consumption of good B, with money balances brought in market B inclusive of the proportional transfer. On the other hand, a type A agent is a net producer in market B, finances her end-of-period money holdings with money balances brought in market B (inclusive of proportional transfers) and sales from production of good B. Substituting $x_B^i$ from the budget constraint into the objective function, the value function simplifies to

$$\max_{\hat{m}^i} W(m^i) = \max_{\hat{m}^i} \left\{ \frac{-\hat{m}^i + (1+\tau) m^i + T^i}{p_B} + v^i + \beta V(\hat{m}^i) \right\}.$$

The optimal choice for $\hat{m}^i$ solves

$$\beta \frac{\partial V(\hat{m}^i)}{\partial \hat{m}^i} - \frac{1}{p_B} \leq 0, \text{ with equality if } \hat{m}^i > 0.$$

As usual in this framework, the value function $W(m)$ is linear in $m$, and the choice of money holdings next period, $\hat{m}$, is independent of current money holdings $m$. The envelope result for both type of agents is

$$\frac{\partial W(m)}{\partial m} = \frac{1+\tau}{p_B}.$$

[16] In the monetary equilibrium, $x_B^i$ is positive for type B agents (they consume) and negative for type A agents (they produce).

**Market A Optimization Problems**

Agents in market A can trade good A and money in a competitive market at market price $p_A$. Type B agents, who are producers in market A, incur a linear production cost to produce $x_A$ units of good A. Their decision problem is

$$V^B(m) = \max_{x_A} \left\{ -x_A + \frac{(1+\tau)(m + x_A p_A)}{p_B} + W^B(0) \right\}.$$

Notice that we have used the envelope result $\frac{\partial W(m)}{\partial m} = \frac{1+\tau}{p_B}$. The first-order condition of type B's problem implies

$$(1+\tau)p_A = p_B. \tag{3}$$

The envelope result is

$$\frac{\partial V^B(m)}{\partial m} = \frac{1+\tau}{p_B}.$$

Type A agents, who are consumers in market A, can buy and consume $x_A$ units of good A. Their value function in market A is

$$\begin{aligned} V^A(m) &= \max_{x_A} \left\{ u(x_A) + \frac{(1+\tau)(m - p_A x_A)}{p_B} + W^A(0) \right\} \\ \text{subject to } p_A x_A &\leq m. \end{aligned}$$

If the cash constraint does not bind, then $u'(x_A) = (1+\tau)p_A/p_B$, which combined with type B's decision, implies $u'(x_A) = 1$, and thus $x_A = x_A^*$. If the cash constraint binds, then $x_A = m/p_A$. In either case, we have

$$\frac{\partial V^A(m)}{\partial m} = \frac{u'(x_A)}{p_A}.$$

**Equilibrium**

We now combine agents' decision problems from market A and market B to derive the equations that characterize the monetary equilibrium. For type B agents, the net marginal value of carrying money to the next market A is

$$\begin{aligned} -\frac{1}{p_B} + \beta \frac{\partial V^B(\hat{m})}{\partial \hat{m}} &= -\frac{1}{p_B} + \beta \frac{1+\tau}{\hat{p}_B} \\ &= \frac{1}{p_B}\left[-1 + \frac{\beta(1+\tau)}{\gamma}\right] < 0. \end{aligned}$$

That is, the money carried by type B agents to market A will be idle in market A and can be used to purchase good B in the next market B. Given $\tau$ is either 0 or $(\gamma - 1)$ (depending on the inflationary schemes), holding idle balances is costly. As a result, it is optimal for type B agents to spend all their money balances in market B and enter market A with zero balances.

For type A agents, the net marginal value of carrying money to the next market A is

$$\begin{aligned}-\frac{1}{p_B} + \beta\frac{\partial V^A(\hat{m})}{\partial \hat{m}} &= -\frac{1}{p_B} + \beta\frac{u'(x_A)}{\hat{p}_A} = -\frac{1}{p_B} + \beta(1+\tau)\frac{u'(x_A)}{\hat{p}_B} \\ &= \frac{1}{p_B}\left[-1 + \frac{\beta(1+\tau)}{\gamma}u'(x_A)\right].\end{aligned}$$

Under the assumption $u'(0) = \infty$, type A agents bring a positive amount of money to market A. In equilibrium, the net marginal benefit of carrying money is zero. Thus, output in market A (per consumer or producer), $x_A$, solves

$$u'(x_A) = \frac{\gamma}{\beta(1+\tau)} = \frac{1+i}{1+\tau}. \tag{4}$$

If $\tau$ is either 0 or $(\gamma - 1)$, type A agents carry just enough money to spend in market A and the cash constraint binds.

Each type A consumes $x_A$ and each type B produces $x_A$ in market A, where $x_A$ solves (4). The market-clearing price in market A, $p_{A,t}$, is

$$p_{A,t} = \frac{M_t}{N x_A}. \tag{5}$$

In market B, the equilibrium price, $p_{B,t}$, is given by (3), and the amount of consumption by each type B agent, $x_B$, is

$$x_B^B = \frac{M_t(1+\tau)/N + T_t^B}{p_{B,t}}, \tag{6}$$

and output per producer (type A) is given by

$$x_B^A = \frac{M_{t+1}/N}{p_{B,t}} = \frac{\gamma}{1+\tau}x_A, \tag{7}$$

where the second equality uses equation (3).[17] Given monetary policy $(M_t, \tau, T_t^B)$, the steady

[17]Notice type B agents hold all of the money supply at the beginning of market B and spend all money, including the amounts from proportional and lump-sum transfers. Similarly, type A agents hold all the money at the end of market B.

Table 1: Monetary Policy Schemes

| | $\gamma$ | $\tau$ | $T_t^B$ |
|---|---|---|---|
| Constant Money Supply (CM) | $= 1$ | 0 | 0 |
| Government Spending (GS) | $> 1$ | 0 | 0 |
| Lump-Sum Transfers (LS) | $> 1$ | 0 | $(\gamma - 1)M_t/N$ |
| Proportional Transfers (PR) | $> 1$ | $\gamma - 1$ | 0 |

state monetary equilibrium is a list of allocations $(x_A, x_B^A, x_B^B)$ and prices $(p_{A,t}, p_{B,t})$ satisfying (3) to (7).

### 3.3 Monetary Policy Schemes

We consider the effect of money growth under three money injection schemes: seigniorage to finance government spending, lump-sum transfers to buyers at the beginning of market B ("helicopter drops"), and transfers proportional to money holdings at the beginning of market B. Table 1 specifies the profile of monetary policies we consider in the context of the model described above.

## 4 Experimental Design and Procedures

We first outline our experimental treatments and hypotheses and then turn to describing our implementation of the experiment.

### 4.1 Treatments

We consider five different treatments to evaluate the effect of the three inflationary policies as outlined in Table 1. The baseline treatment features a laissez-faire policy with a constant money supply (this treatment is labeled CM). We then design three treatments with the same money growth rate at $\gamma - 1 = 30\%$, but each with a different implementation scheme for money injection: via government spending, lump-sum transfers or proportional transfers. We label them as GS-30, LS-30 and PR-30, respectively. In terms of real effects, money growth implemented by government spending and lump-sum transfers has detrimental effects on output and welfare relative to the Constant Money treatment. In these implementations, inflation should act like a tax on real money holdings. The third policy scheme with proportional transfers provides additional testing of the inflation tax channel. Under this scheme, the distortionary effect of inflation is neutralized by the proportional transfer, and output and welfare remain the same as in the Constant Money treatment. That is, the proportional transfer compensates agents for the inflation tax, and thus there are no real effects. Finally, to allow for a more exhaustive exploration of the quantity theory of money and the effect of inflation, we run a treatment with a lower money growth rate at $\gamma - 1 = 15\%$, where new money is injected to finance government spending; this treatment is labeled GS-15.[18]

Other parameters are chosen as follows. The discount factor is set to $\beta = 0.9$. The period utility functions for type A and B agents are respectively

$$U^A = \underbrace{A\frac{x_A^{1-\eta}}{1-\eta}}_{\text{market A}} - \underbrace{x_B}_{\text{market B}} \text{ and } U^B = \underbrace{-x_A}_{\text{market A}} + \underbrace{v_0 + x_B}_{\text{market B}};$$

where $A = 2.6563$, $\eta = 0.37851$, and $v_0 = 8$ in CM and PR-30 treatments, $v_0 = 6$ in GS-15, $v_0 = 5$ in GS-30 and $v_0 = 3.5$ in LS-30. The parameters $A$ and $\eta$ were chosen to obtain salient differences in the theoretical predictions and integer values for equilibrium quantities for $\gamma = 1$ and $\gamma = 1.3$. The parameter $v_0$ was chosen to (roughly) equalize equilibrium expected payoffs for type A and type B subjects.

Table 2 summarizes the steady state equilibrium predictions for output, prices, inflation and welfare for each treatment, which we use to formulate the main hypotheses we test with our experiments. Equilibrium prices and quantities are calculated from equations (3) to (7). Welfare is calculated as the sum of period utilities for all agents. Note that since agents' utilities are linear in market B, welfare is simply the sum of trading surpluses related to the consumption by each individual type A agent. The last column of Table 2 provides the welfare ratio, denoted $W$, which measures efficiency relative to the first-best quantity of output in market A, $x_A^* = 13.2$:

$$\mathcal{W} \equiv \frac{\sum_i [u(x_{A,i}) - x_{A,i}]}{N[u(x_A^*) - x_A^*]}.$$

Theory predicts GS-30 and LS-30 yield the same stationary equilibrium where the inflation rate is equal at the constant money growth rate, $100(\gamma - 1)\%$. Quantities traded and welfare for all inflationary treatments are lower than in the CM treatment, except for PR-30,

[18]The money growth rates, $\gamma = 1.15$ and $\gamma = 1.3$, are set so that the effects of money growth are salient to subjects. Due to budget concerns, we explored the effect of lower money growth only under the government spending scheme.

Table 2: Equilibrium Predictions

| Treatment | $x_A$ | $x_B$ | $p_{At}$ | $p_{Bt}$ | Inflation | Welfare Ratio |
|---|---|---|---|---|---|---|
| CM | 10 | 10 | 0.5 | 0.5 | 0 | 0.98 |
| GS-15 | 6.91 | 7.95 | $0.7233 * 1.15^{t-1}$ | $0.7233 * 1.15^{t-1}$ | 15% | 0.91 |
| GS-30 | 5 | 6.5 | $1.3^{t-1}$ | $1.3^{t-1}$ | 30% | 0.82 |
| LS-30 | 5 | 6.5 | $1.3^{t-1}$ | $1.3^{t-1}$ | 30% | 0.82 |
| PR-30 | 10 | 10 | $0.5 * 1.3^{t-1}$ | $0.5 * 1.3^{t}$ | 30% | 0.98 |

where the expansion of money supply has no real effects. This holds because inflation acts like a tax on real money holdings in GS-30 and LS-30, while the effect of the inflation tax is neutralized in PR-30 by the interest paid on money balances at the rate of inflation. In addition, output and welfare in GS-30 should be lower than in GS-15.

## 4.2 Hypotheses

We explore the following questions: Do anticipated changes in money supply transfer to prices? If there is inflation, do subjects perceive it like a tax in the Lump-Sum and Government Spending treatments, and realize that the inflation tax is neutralized by transfers in the Proportional Transfers treatment? Based on the theoretical predictions in Table 2, we formulate the following three hypotheses about inflation, quantities traded, and welfare across treatments. The first hypothesis concerns the quantity theory of money, which states that the general price of goods is directly proportional to the amount of money in circulation. In other words, changes in money growth have one-to-one changes in inflation. The second and third hypotheses focus on the real effects of money supply changes on output and welfare, respectively. In the formulation of the hypotheses, for each treatment $i$, we let $\pi_A^i$ and $\pi_B^i$ denote the inflation rate in markets A and B, $x_A^i$ output in market A, and $\mathcal{W}^i$ the welfare ratio.[19]

**Hypothesis 1.** Higher money growth rates lead to higher inflation rates in markets A and B. Specifically, inflation rates in markets A and B are higher in GS-15, GS-30, LS-30, and PR-30 than in the CM treatment. In addition, inflation rates are lower in GS-15 than in GS-30.

$$\pi_A^{CM} < \pi_A^{GS-15} < \pi_A^{GS-30} = \pi_A^{LS-30} = \pi_A^{PR-30},$$

$$\pi_B^{CM} < \pi_B^{GS-15} < \pi_B^{GS-30} = \pi_B^{LS-30} = \pi_B^{PR-30}.$$

[19] We focus on output in market A because it determines the total welfare.

**Hypothesis 2.** Output in market A is lower in GS-15, GS-30, and LS-30 relative to the CM and PR-30 treatments.

$$x_A^{CM} = x_A^{PR-30} > x_A^{GS-15} > x_A^{GS-30} = x_A^{LS-30}.$$

**Hypothesis 3.** Welfare is lower in GS-15, GS-30, and LS-30 relative to the CM and PR-30 treatments.

$$\mathcal{W}^{CM} = \mathcal{W}^{PR-30} > \mathcal{W}^{GS-15} > \mathcal{W}^{GS-30} = \mathcal{W}^{LS-30}.$$

### 4.3 Experimental Procedures

In this subsection, we describe the general experimental procedure and how we implement three ingredients of the theoretical model that underpins our experimental study: infinite horizon with discounting, competitive markets and money growth.

The experiments in this study were conducted at Purdue University and Indiana University in 2018 and 2019 (see Table 3). Participants were undergraduate students at Purdue University and Indiana University across genders and majors.[20] We adopt a between-subjects design where each session of the experiment consists of a new group of subjects making decisions under a single parameter set. For each treatment, we conduct four sessions.[21] For each session, the total number of subjects is $2N = 10$, equally split between type A and type B agents, with the exception of one session where $2N = 8$ since fewer subjects showed up for that session. No subject participated in more than one session of the experiment, although some subjects may have participated previously in other economics experiments.

The total length of a session ranged from 100 to 120 minutes, though all subjects were recruited for 2 hours. Participants received a \$5 show-up payment plus earnings from the experiment. Points earned by subjects in the experiments were converted to dollars at the exchange rate 0.15 points per dollar except for three sessions in the GS-30 treatment.[22]

[20]The demographic composition of the subjects are very similar across Purdue and Indiana University, except slightly more Liberal Arts majors at Indiana University than Purdue due to the presence of engineering majors at Purdue. The experimental results are not noticeably different across the two universities.

[21]We used theoretical predictions and data from the closest treatment in Duffy and Puzzello (2014a) to compute the power of the test for differences in output between the CM, LS-30, and GS-30 treatments. For a sample size of 4 sessions per treatment and a probability level of 5%, the power is 78% (details available upon request).

[22]In the Government Spending treatment, the government agents take away resources from the economy so we initially used a slightly higher exchange rate of 0.2 to make subjects' point earnings more commensurate across treatments. We then decided to keep the 0.15 exchange rate constant across subsequent sessions and treatments for the sake of comparability. The exchange rate does not affect our theoretical predictions.

Subjects were paid for all periods of all sequences. Average earnings across all treatments were $25.67.

Table 3: Session Characteristics

| Treatment | Session | Date | Subjects | Location | Sequence Lengths |
|---|---|---|---|---|---|
| Constant Money | 1 | 8/3/2018 | 8 | Purdue | 9, 15 |
| (CM) | 2 | 8/24/2018 | 10 | Indiana | 6, 8, 2, 16 |
| | 3 | 8/29/2018 | 10 | Indiana | 13, 10, 5 |
| | 4 | 9/5/2018 | 10 | Purdue | 5, 6, 4 |
| Government Spending 15 | 1 | 3/27/2019 | 10 | Purdue | 9, 15 |
| (GS-15) | 2 | 3/27/2019 | 10 | Purdue | 6, 8, 2 |
| | 3 | 3/27/2019 | 10 | Indiana | 13, 10, 5, 11 |
| | 4 | 3/27/2019 | 10 | Indiana | 5, 6, 4 |
| Government Spending 30 | 1 | 7/25/2018 | 10 | Purdue | 9, 15 |
| (GS-30) | 2 | 8/27/2018 | 10 | Indiana | 6, 8, 2, 16 |
| | 3 | 9/19/2018 | 10 | Purdue | 13, 10 |
| | 4 | 9/4/2018 | 10 | Purdue | 5, 6, 4, 1 |
| Lump Sum Transfers 30 | 1 | 9/26/2018 | 10 | Purdue | 9, 15 |
| (LS-30) | 2 | 9/27/2018 | 10 | Purdue | 6, 8, 2 |
| | 3 | 10/10/2018 | 10 | Purdue | 13, 10, 5 |
| | 4 | 10/23/2018 | 10 | Purdue | 5, 6, 4 |
| Proportional Transfers 30 | 1 | 11/27/2018 | 10 | Purdue | 9, 15 |
| (PR-30) | 2 | 11/27/2018 | 10 | Purdue | 6, 8, 2 |
| | 3 | 12/7/2018 | 10 | Purdue | 13, 10 |
| | 4 | 12/7/2018 | 10 | Purdue | 5, 6, 4 |

Each session included instructions, a comprehension quiz on the instructions (see Appendix C for the instructions and quiz), and the experiment. Upon entering the laboratory, participants were assigned a computer station and given a written copy of the instructions. Participants then completed a comprehension quiz about the instructions. After completing the quiz, the experimenter went over the correct answers, answered questions individually, and began the experiment. We purposely spent a large portion of time on this phase of the experiment (typically 45 minutes to an hour) to ensure subjects' comprehension. All parts of the experiment were programmed with z-Tree (Fischbacher 2007).

Further, behavior in the session with the 0.15 exchange rate was comparable with behavior observed in the sessions employing the 0.2 exchange rate.

In the experiments, a period consists of market A followed by market B. The mapping of production and consumption decisions to points is described in detail to subjects in the written instructions and presented to subjects in table form in both the instructions and on their computer screens. Furthermore, subjects can also see previous periods' prices for both markets, which allows them to observe price changes over time.[23] See Figure 1 for a sample screenshot.

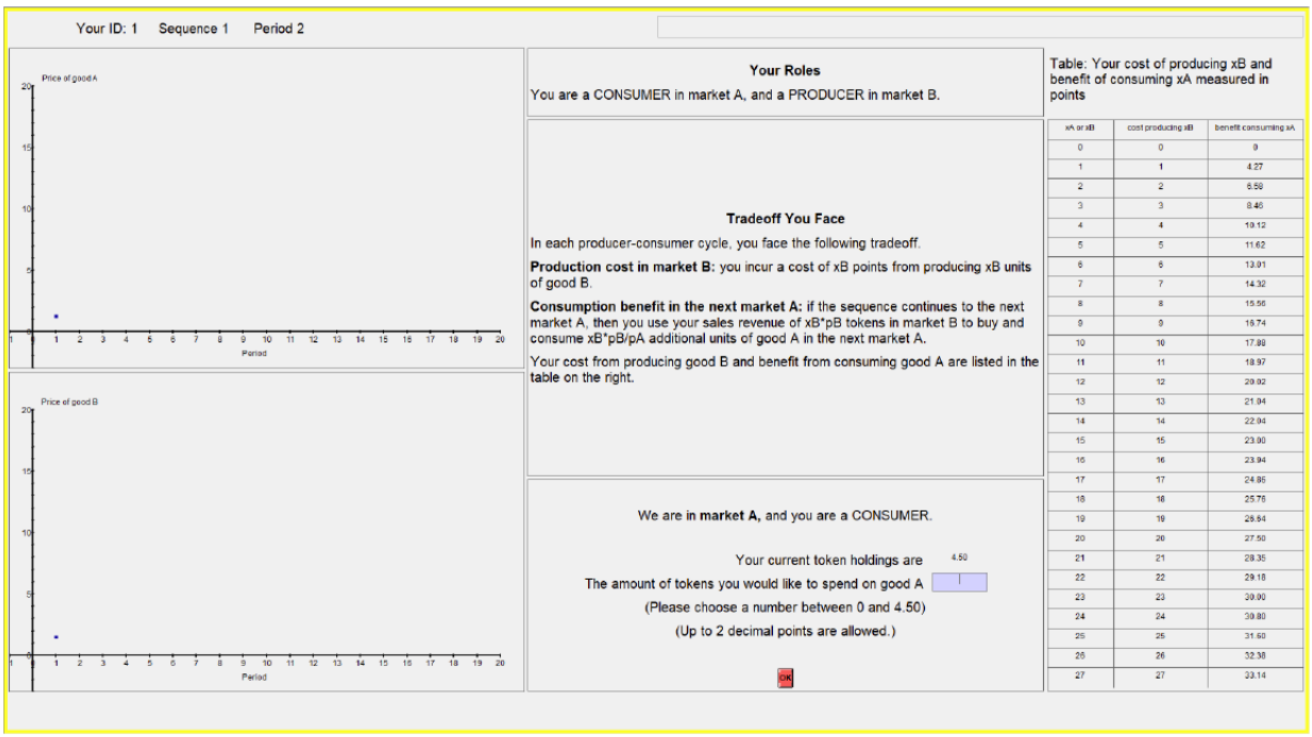


Figure 1: Sample Decision Screen of Experiment

**Indefinite Horizon.** Our theoretical model in Section 3 features an infinite horizon where all agents have a constant discount factor $\beta$. The standard approach to implementing an infinite horizon in the laboratory follows Roth and Murnighan (1978). Each session consisted of several sequences which in turn consisted of an indefinite number of periods. After each

[23]Notice subjects would not able to observe previous periods' prices if the pricing mechanism was bilateral bargaining. This aspect of our design is an important departure from Duffy and Puzzello (2018), where prices are determined through take-it-or-leave-it-offers by buyers. While this feature does not affect the steady state theoretical predictions, it may affect behavior. We conjecture this may be one reason why our results are closer to theoretical predictions relative to what Duffy and Puzzello (2018) find. An exhaustive exploration of how the trading protocol affects the degree to which monetary policy is successful in producing the desired result, is interesting in itself and is left for further research.

period, the sequence continues with a fixed probability equal to $\beta = 0.9$. We implemented the indefinite horizon with a block random termination procedure similar to Fréchette and Yuksel (2017). Subjects played a "block" 10 periods and were informed about the termination period at the end of the block. If the sequence had ended within the block, then decisions after the termination period were invalid. If the sequence had not ended by period 10, then from period 11 onward, subject were informed about whether the sequence would continue after each period.[24] Sessions averaged 32.3 total periods with a median of 3 sequences per session. Table 3 summarizes the sequence lengths for each session.[25]

**Market Game.** Prices are endogenously determined by subjects' decisions in the experiment. This feature allows us to explore whether and how changes in the money supply affect price formation. To implement competitive pricing in markets A and B, subjects participate in a market game as in Shapley and Shubik (1977), which provides non-cooperative foundations to competitive equilibrium outcomes (see e.g., Arifovic 1996; Bernasconi and Kirchkamp 2000; Duffy, Matros, and Temzelides 2011; Ding and Puzzello (2020); Duffy and Puzzello 2014ab, 2018; among others, for implementations of market games in laboratory economies). Another advantage of the market game is that it allows us to precisely control the injection of money, and thus the money supply growth rate, in the government spending treatment. In both markets, producers submit a quantity to produce ($x_A$ or $x_B$) while consumers submit a bid of tokens for good A or B ($b_A$ or $b_B$). Subjects make these decisions in isolation and do not observe current actions of other participants. The market price in each market is then computed as

$$p = \frac{\sum_i b_i}{\sum_i x_i} = \frac{\text{Total Tokens Bid}}{\text{Total Amount Produced}},$$

[24]Our procedure is slightly different from the one proposed by Fréchette and Yuksel (2017), where subjects would always start a new block after one was over. In our procedure, if the sequence did not terminate by the end of the 10-period block, subjects received feedback, in each period afterwards, on whether the sequence continued or not. That is, we did not start a new 10-period block after the first block was over. We adopted this procedure because it allowed us to potentially fit more sequences in a session: after the first block, the sequence could stop anytime instead of at the end of another 10-period block. The same design is used by Duffy, Jiang, and Xie (2019) in experimental asset markets.

[25]In a follow-up project Jiang, Puzzello, and Zhang (2020), we propose a new method for implementing infinite horizon environments in the lab using the discount factor interpretation to back out subjects' continuation value following a period of deterministic decisions. In a similar set up as in this one but only with a constant money supply, we then compare the results of our new method with the block design and random termination methods commonly used in the literature. We do not find substantial differences across implementation methods. Davis et al. (2019) study finite horizon environments where fiat money is valued, but these environments are not well suited to study inflationary monetary policies.

where $b_i$ and $x_i$ are the individual bids and production decisions of consumers and producers, respectively, for subject $i$. If the total amount of tokens bid or the total amount produced is zero, no trade takes place. If the price is positive, buyers consume an amount equal to their bid divided by the market price and their point total increases as specified by the utility function in each market, while their token total decreases by the amount bid. Producers lose points from production as specified by the production function but their token total increases by the amount produced times the market price.

**Schedule of Token Increases.** In all treatments, type A agents (who are consumers in market A) are endowed with 5 tokens at the start of a new sequence. In the Constant Money treatment, the total token supply is fixed at $5 \times N$. Otherwise, the token supply increases by $100(\gamma - 1)\%$ in market B of each period (i.e. either 15% or 30%). In the Government Spending treatments, we introduce computerized "robots" in market B that create new tokens and use them to purchase good B. Subjects are informed these robots were pre-programmed and intervene in market B only to create new tokens and use them to buy goods.[26] In the Lump-Sum Transfers treatment, consumers in market B receive a lump-sum transfer of tokens at the start of each market B. In the Proportional Transfers treatment, all agents receive a 30% transfer of tokens, proportional to their token holdings, at the start of each market B. That is, in all treatments, increases in money supply are injected before trading in market B. Importantly, all schemes are publicly known and described in detail to the subjects in the instructions. For example, in the Lump-Sum Transfers treatment, subjects were informed about lump-sum transfers' amounts in each period. Similarly, in the Government Spending treatment subjects knew how many tokens robots buyers spent in each period. The comprehension quiz on the instructions also tested subjects' knowledge about how a given scheme would impact the supply of tokens (see Appendix C for the instructions and quiz).

# 5 Results

We organize our results into a series of findings that mirror our hypotheses. Namely, we first discuss the impact of changes in the money supply on prices, and then on output and welfare.

[26] In the treatments with government spending, new money is used to purchase output from subjects and the purchased output is not distributed back to subjects. In follow up work, we plan to explore an implementation where subjects' production is redistributed back to subjects via real lump-sum transfers.

**Finding 1.** *Inflation rates in markets A and B are higher in the GS-15, GS-30, LS-30, and PR-30 treatments than in the CM treatment; inflation rates are lower in GS-15 than in GS-30, LS-30 and PR-30.*

Recall the theoretical steady state inflation rate is 0% in treatment CM, 15% in treatment GS-15 and 30% in the remaining treatments. To estimate the inflation rate in the experimental economies, we regress the natural log of the price level in market A or B on the time period within sequences. The coefficient on the time period captures the growth rate of the price level and hence it is an estimate of the inflation rate. Tables 4 and 5 show the estimates for inflation in market A and market B for each treatment, pooling observations from all sessions within the same treatment.[27] Figures 2 and 3 graph average estimated inflation rates with 95% confidence intervals for the three treatments. To compare the inflation rate in different treatments, we also estimate the differences in inflation rates between a pair of treatments. The results are summarized in Table 6 for market A and Table 7 for market B, where each entry in a cell represents the estimate of the inflation rate in the column treatment minus the inflation rate in the row treatment.

Consistent with Hypothesis 1 and the quantity theory of money, Figures 2 and 3 show higher money growth rates are associated with higher inflation rates in the experimental economies. So, changes in the money supply do transfer to changes in prices, which was not ex-ante guaranteed, as prices are endogenously determined by subjects' choices. As shown in Tables 6 and 7, average inflation in market A (B) is 9.7% (10.9%) higher in GS-15, 20.6% (20.5%) higher in GS-30, 17.2% (19.5%) higher in LS-30, and 18.9% (22.9%) higher in PR-30 relative to the CM treatment. The inflation rate in market A (B) is 10.9% higher in GS-30, 7.5% higher in LS-30 and 9.5% higher in PR-30 relative to GS-15. Inflation rates are close to each other among the three treatments with 30% money growth, even though the inflation rate is slightly higher in GS-30 than LS-30.

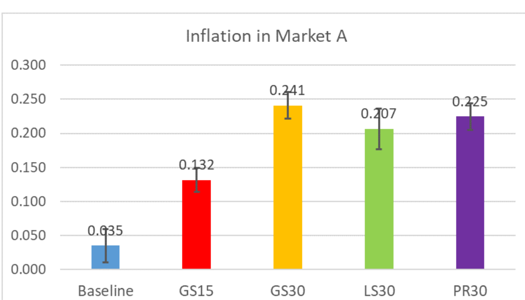


Figure 2: Average Market A Inflation Rates

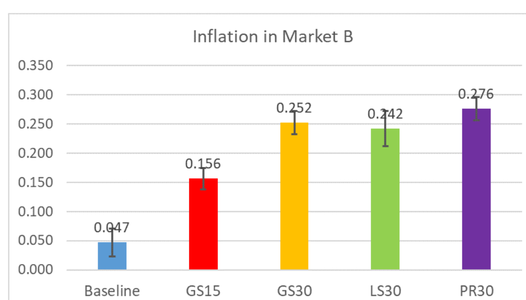


Figure 3: Average Market B Inflation Rates

[27] For more details, see Table A.4 in Appendix A for estimates of inflation by session and Figure B.2 in Appendix B for the time paths of prices by session.

Table 4: Market A Inflation Estimates, by Treatment

| Variables | $\ln(p^{CM})$ | $\ln(p^{GS-15})$ | $\ln(p^{GS-30})$ | $\ln(p^{LS-30})$ | $\ln(p^{PR-30})$ |
|---|---|---|---|---|---|
| Period | 0.035*** | 0.132*** | 0.241*** | 0.207*** | 0.225*** |
| | (0.00122) | (0.00900) | (0.00100) | (0.00152) | (0.00100) |
| Constant | −1.370*** | −0.923*** | −0.822*** | −1.070*** | −1.298*** |
| | (0.0841) | (0.0665) | (0.02743) | (0.0105) | (0.0604) |
| Observations | 134 | 129 | 134 | 118 | 108 |
| R-squared | 0.068 | 0.628 | 0.821 | 0.646 | 0.817 |

Notes.
(1) Robust standard errors in parentheses.
(2) * p-value < 0.10, ** p-value < 0.05, *** p-value < 0.01.

Table 5: Market B Inflation Estimates, by Treatment

| Variables | $\ln(p^{CM})$ | $\ln(p^{GS-15})$ | $\ln(p^{GS-30})$ | $\ln(p^{LS-30})$ | $\ln(p^{PR-30})$ |
|---|---|---|---|---|---|
| Period | 0.047*** | 0.156*** | 0.252*** | 0.242*** | 0.276*** |
| | (0.00146) | (0.00109) | (0.00102) | (0.00128) | (0.00132) |
| Constant | −1.322*** | −0.859*** | −0.752*** | −0.793*** | −1.176*** |
| | (0.0867) | (0.0670) | (0.0806) | (0.0846) | (0.0874) |
| Observations | 134 | 129 | 134 | 118 | 108 |
| R-squared | 0.087 | 0.608 | 0.823 | 0.763 | 0.787 |

Notes.
(1) Robust standard errors in parentheses.
(2) * p-value < 0.10, ** p-value < 0.05, *** p-value < 0.01.

Table 6: Estimated Difference in Market A Inflation

| | GS-15 | GS-30 | LS-30 | PR-30 |
|---|---|---|---|---|
| CM | 0.097*** | 0.206*** | 0.172*** | 0.189*** |
| | (0.0152) | (0.0158) | (0.0195) | (0.0158) |
| GS-15 | | 0.109*** | 0.075*** | 0.093*** |
| | | (0.0135) | (0.0176) | (0.134) |
| GS-30 | | | −0.034* | -0.017 |
| | | | (0.0181) | (0.0141) |
| LS-30 | | | | 0.018 |
| | | | | (0.0182) |

Notes.
(1) Each entry in a cell represents the estimate of the inflation rate in the column treatment minus the inflation rate in the row treatment.
(2) Robust standard errors in parentheses.
(3) * p-value < 0.10, ** p-value < 0.05, *** p-value < 0.01.

Table 7: Estimated Difference in Market B Inflation

| | GS-15 | GS-30 | LS-30 | PR-30 |
|---|---|---|---|---|
| CM | 0.109***<br>(0.0183) | 0.205***<br>(0.0178) | 0.195***<br>(0.0195) | 0.229***<br>(0.0197) |
| GS-15 | | 0.095***<br>(0.0149) | 0.085***<br>(0.0168) | 0.119***<br>(0.0171) |
| GS-30 | | | -0.010<br>(0.0163) | 0.024<br>(0.0166) |
| LS-30 | | | | 0.034*<br>(0.0184) |

Notes.
(1) Each entry in a cell represents the estimate of the inflation rate in the column treatment minus the inflation rate in the row treatment.
(2) Robust standard errors in parentheses.
(3) * p-value < 0.10, ** p-value < 0.05, *** p-value < 0.01.

While we find support for the directional predictions of Hypothesis 1, overall inflation rates tend to deviate slightly from the theoretical point predictions. Table A.4 in Appendix A shows the estimated inflation rate is statistically different from the theoretical point prediction in most experimental sessions. From Tables 4, 5 and A.4, the magnitude of the deviation in market A (market B) averages 3.5% (4.7%) in the CM treatment, -1.8% (0.6%) in GS-15, -5.9% (-4.8%) in GS-30, -9.3% (-5.8%) in LS-30 and -7.5% (-2.4%) in PR-30. Namely, the overall inflation rate is slightly higher than the point prediction in treatment CM, while the reverse is true for the three inflationary treatments with 30% money growth (the deviation is very small and in the opposite direction in the two markets for treatment GS-15).

We can gain some insights about the observed deviations from the point prediction of the inflation rate by examining the time trends of the level of output (Tables 10 and A.3), the buyer's spending ratio (Table A.8), and the fraction of money held in the hands of buyers (Table A.9). The slightly positive inflation in treatment CM can be attributed to the slight downward trend in output in market A and the upward trend in the spending ratio and the fraction of money held by buyers in market B.[28] In the three treatments with 30% money growth, the quantities produced in market A were stable over time, and the slightly lower observed inflation relative to the theory prediction could be largely attributed to decreasing buyers' money holdings at the aggregate level as a fraction of total money supply, especially in market A. This effect is weaker in the GS-30 treatment relative to LS-

[28]A mildly positive inflation rate is also observed by Duffy and Puzzello (2018) and Jiang, Puzzello and Zhang (2020) in their treatments with fixed money supply.

30 and PR-30 as indicated by the smaller coefficient on time period in Table A.9. This may explain why inflation rates in market A are higher in the GS-30 treatment, where money injections occurred through automatic spending, and thus ended up in the holdings of market A consumers.[29] To summarize, we find overall support for qualitative predictions of the theory but, perhaps not surprisingly we observe some deviations from point predictions.[30]

We next discuss whether inflationary policies have real effects on output and welfare. In what follows, we focus on market A output since it is the main variable affecting welfare computations (we discuss the effects on market B output in Appendix A).

**Finding 2.** *Market A output is significantly lower in GS-15, GS-30, and LS-30 than in CM. In addition, market A output is significantly lower in GS-30 than in LS-30.*

To validate Hypothesis 2, we regress market A average output (across producers in a single period) on treatment dummies and report the results in Table 8. The constant term from the regression is average market A output in the CM treatment while the coefficients on the treatment variables correspond to the marginal effect of the corresponding treatment. Similar to the analysis on inflation, we also estimate differences in average output between each pair of treatments, and report the results in Table 9 (each entry in a cell represents the estimate of the average market A output in the column treatment minus the average output in the row treatment).[31] Figure 4 summarizes the average quantity produced in markets A across sessions for each treatment where the bands correspond to 95% confidence intervals.

Recall theory predicts output in market A is 10 in CM and PR-30, 6.91 in GS-15, and 5 in GS-30 and LS-30. The regression results confirms market A output is significantly lower in GS-15, GS-30, and LS-30 relative to the CM treatment. In addition, consistent with theory, market A output is not significantly different between PR-30 and CM. Further, output in GS-30 is significantly lower than in GS-15. These results are broadly consistent with the directional hypotheses from the theoretical predictions, confirming the adverse effects of inflation on output. Regarding point predictions, average output in Market A is strikingly close and not significantly different from the theoretical prediction of 10 in CM and PR-30. On the other hand, output in all the inflationary treatments with real effects, namely GS-15,

[29]In treatment PR-30, there is a notable decrease in average output in market B over time, which could lead to higher observed inflation relative to theory. However, this effect is neutralized by the decreasing spending ratio and increasing fraction of money held by consumers. The overall market B inflation in treatment PR-30 is 27.6%, which is close to the theoretical prediction of 30% inflation.

[30]It is not uncommon to focus on directional hypotheses. We think that the expectation that theoretical point predictions hold implies an extremely strict test of a theory.

[31]Notice the difference in average output between the CM and other treatments can be directly inferred from Table 8.

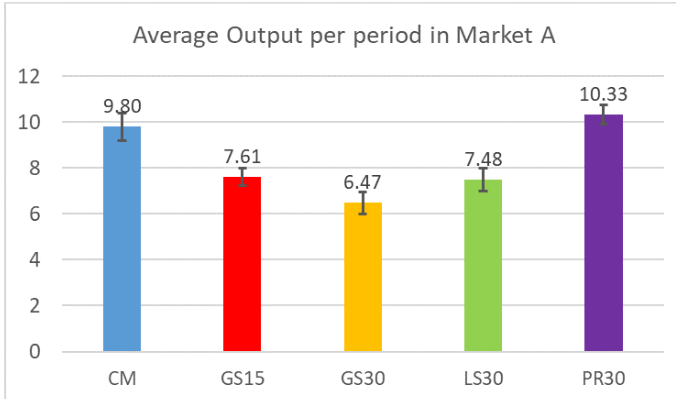


Figure 4: Average Market A Output

Notes. Theory predicts output in market A is 10 in CM and PR-30, 6.91 in GS-15, and 5 in GS-30 and LS-30.

GS-30 and LS-30, is higher than the theoretical prediction of 6.91 and 5. This suggests that, while inflation has adverse effects on output, they are not as severe as predicted by the theory (see Table A.5 for more details, including the estimated output in market A and deviation from theoretical point predictions for each session). This may be in part due to the fact that inflation rates are slightly lower than predicted, implying a lower inflation tax (see Table 4 and Table 5).

An outcome from the experiments not predicted by theory is that market A output is significantly lower in GS-30 than in LS-30 (see Figure 4 and Table 9). This indicates the inflationary implementation scheme matters, as output is affected more adversely in GS-30 than in LS-30. This result may be attributed in part to the slightly higher inflation rates, and therefore inflation taxes, in GS-30 relative to LS-30 (see the discussion on Finding 1 above). Another potential reason for the higher observed output in LS-30 is type B subjects may perceive they are compensated with additional tokens for their earnings in market A. In theory, the transfers are lump sum and should not affect their production decisions (i.e. type B subjects would receive the transfer even if they do not produce in market A), but it is possible that subjects in the lab may perceive that they are compensated for their production in market A which would tame the adverse effect of the inflation tax.

**Finding 3.** *Welfare is significantly lower in GS-15 and GS-30 than in CM. Welfare in LS-30 is significantly higher than in GS-30.*

Figure 5 reports average welfare ratios across treatments where the bands again correspond to 95% confidence intervals. We also regress the welfare ratio on treatment dummies and report the results in Table 11. The results from Figure 5 and Table 11 confirm that

Table 8: Regression of Average Market A Output on Treatment Dummies

| Variables | Avg. Market A Output |
|---|---|
| GS-15 | $-2.193^{***}$ |
| | (0.358) |
| GS-30 | $-3.326^{***}$ |
| | (0.389) |
| LS-30 | $-2.319^{***}$ |
| | (0.397) |
| PR-30 | 0.529 |
| | (0.375) |
| Constant | $9.800^{***}$ |
| | (0.303) |
| Observations | 623 |
| R-squared | 0.218 |

Notes.
(1) Robust standard errors in parentheses.
(2) * p-value < 0.10, ** p-value < 0.05, *** p-value < 0.01.

Table 9: Estimated Difference in Average Market A Output

| | GS-30 | LS-30 | PR-30 |
|---|---|---|---|
| GS-15 | $-1.133^{***}$ | -0.126 | $2.721^{***}$ |
| | (0.310) | (0.320) | (0.292) |
| GS-30 | | $1.007^{***}$ | $3.854^{***}$ |
| | | (0.354) | (0.330) |
| LS-30 | | | $2.847^{***}$ |
| | | | (0.339) |

Notes.
(1) Each entry in a cell represents the estimate of the average market A output in the column treatment minus the average market A output in the row treatment.
(2) Robust standard errors in parentheses.
(3) * p-value < 0.10, ** p-value < 0.05, *** p-value < 0.01.
(4) Note that the difference in average output between the CM and other treatments can be also directly read from Table 8.

Table 10: Time Trend in Average Market A Output

| | Obs. | Coef. | Robust Std. Err. |
|---|---|---|---|
| CM | 134 | -0.234 *** | 0.085 |
| GS-15 | 129 | 0.060 | 0.057 |
| GS-30 | 134 | 0.019 | 0.069 |
| LS-30 | 118 | 0.126 | 0.078 |
| PR-30 | 108 | 0.103 | 0.068 |

Notes.
(1) Robust standard errors in parentheses.
(2) * p-value < 0.10, ** p-value < 0.05, *** p-value < 0.01.

welfare is significantly lower in GS-15 and GS-30 than in CM, while welfare in PR-30 is not significantly different from CM. Similar to our findings on market A output, welfare in LS-30 is significantly higher than in GS-30, which suggests inflationary schemes with government spending have stronger real effects than with lump-sum transfers. In addition to lower average output, we also observe higher dispersion in consumption (across buyers and time) in GS-30 than in LS-30, as captured by a higher coefficient of variation in GS-30 (see Table 13). Higher consumption dispersion also contributes to generating a lower welfare.

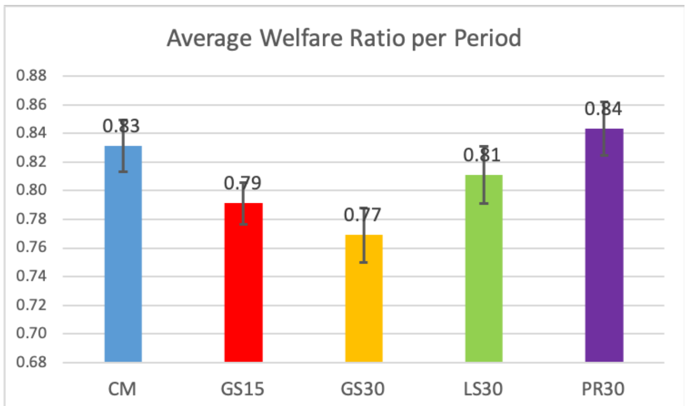


Figure 5: Welfare Ratio

Notes. Theory predicts welfare ratio is 0.98 in CM and PR-30, 0.91 in GS-15, and 0.82 in GS-30 and LS-30.

Table 11: Regression of Welfare Ratio on Treatment Dummies

| Variables | Welfare Ratio |
|---|---|
| GS-15 | $-0.040^{***}$ |
| | (0.012) |
| GS-30 | $-0.062^{***}$ |
| | (0.013) |
| LS-30 | $-0.020$ |
| | (0.014) |
| PR-30 | 0.012 |
| | (0.013) |
| Constant | $0.827^{***}$ |
| | (0.009) |
| Observations | 623 |
| R-squared | 0.066 |

Notes.
(1) Robust standard errors in parentheses.
(2) * p-value $< 0.10$, ** p-value $< 0.05$, *** p-value $< 0.01$.

Point predictions from the theory are not supported as welfare is significantly lower than predicted (see Table A.6 for estimated welfare ratio and deviation from theoretical point predictions for each session and treatment), with the exception of the LS-30 treatment where welfare is not significantly different from the theoretical prediction of 0.82. Also note that the low welfare relative to theory prediction is mainly due to consumption dispersion (dispersion is positive in the experiment while zero in theory). As shown in Table A.6, removing consumption dispersion and evaluating welfare ratio assuming every buyer consumes the average output would bring the welfare ratio close to or even higher than the theoretical prediction (recall that the observed inflation tends to be lower and output tends to be higher than theoretical predictions; see Table A.5).

To summarize, we find inflation tends to decrease welfare in treatments predicting real effects, and the detrimental effect can be attributed to both decreased aggregate output and increased consumption dispersion among consumers. Welfare is computed by summing up the utility function of all traders. Welfare is decreasing in consumption dispersion because of the concavity of the utility function of market A traders. Further, the implementation details of money injections matter, as welfare is more adversely affected in treatments with government spending relative to lump sum transfers. This result may be explained by the combination of two factors: higher inflation and higher consumption dispersion in GS-30 than in LS-30. While higher consumption dispersion is not predicted by the model, we conjecture that it is affected by the implementation method. In contrast to the GS-30 treatment, in LS-30, subjects received lump-sum transfers that help reduce money holdings' dispersion and, in turn, consumption dispersion.

Table 12: Estimated Difference in Welfare Ratio

| | GS-30 | LS-30 | PR-30 |
|---|---|---|---|
| GS-15 | $-0.022^{*}$ | 0.020 | $0.052^{***}$ |
| | (0.012) | (0.012) | (0.012) |
| GS-30 | | $0.042^{***}$ | $0.074^{***}$ |
| | | (0.014) | (0.013) |
| LS-30 | | | $0.032^{**}$ |
| | | | (0.014) |

Notes.
(1) Each entry in a cell represents the estimate of the welfare ratio in the column treatment minus the welfare ratio in the row treatment.
(2) Robust standard errors in parentheses.
(3) * p-value < 0.10, ** p-value < 0.05, *** p-value < 0.01.
(4) Note that the difference in average welfare ratio between the CM and other treatments can be also directly read from Table 11.

Table 13: Individual Consumption in Market A: Summary Statistics, by Treatment

| Treatment | Obs. | Mean | std | CoV. |
|---|---|---|---|---|
| Baseline | 645 | 9.687 | 6.763 | 0.698 |
| GS-15 | 645 | 7.607 | 6.253 | 0.822 |
| GS-30 | 670 | 6.474 | 5.311 | 0.820 |
| LS-30 | 590 | 7.481 | 5.358 | 0.716 |
| PR-30 | 540 | 10.329 | 7.485 | 0.725 |

# 6 Conclusion

We develop an experimental framework to study the quantity theory of money and the real effects of expected inflation, implemented through anticipated changes in the money supply. In particular, we test the classic view that inflation has detrimental effects on allocations and welfare by taxing monetary exchange. We examine three different schemes to engineer money growth, where new money is injected to finance government spending, lump-sum transfers (or helicopter drops), and proportional transfers. The quantity theory of money predicts money growth translates into inflation. In terms of real effects, money growth through government spending and lump-sum transfers result in the same detrimental effects on output and welfare. Under proportional transfers, the inflation tax is compensated and neutralized by the proportional transfer so inflation does not affect the real economy.

Our findings from the experimental economies are largely consistent with theory, though we also obtain results that depart from the model. First, we find broad support for the quantity theory of money, i.e., inflation rates (endogenously determined in the laboratory economy) track money growth rates across sessions. Also consistent with theory, inflation engineered to finance government spending and lump sum taxes has detrimental effects on output and welfare, but is neutral if used to finance transfers proportional to money holdings. A deviation from theory is that output and welfare are lower in the treatment with government spending than the treatment with lump sum transfers, which suggests that the real effects of expected inflation depend on the scheme of money injections.

Many advanced economies are currently experiencing low nominal interest rates, which constrains monetary policy in offsetting negative shocks. While this has generated some discussion of raising the inflation target, mindful of the detrimental effects of high inflation, central banks have so far been cautious about implementing such changes (Bullard 2012). Our study focuses on the positive implications of inflationary policy and shows that the inflation tax channel works as intended in a controlled laboratory economy, where internal validity holds. While we focus on simpler markets than naturally occurring ones, the inflation tax channel is explicit in our framework.

Finally, we would like to point out that the framework we develop in this paper is well grounded for experimental methods and can be enriched to study other important questions in monetary economics, including the effects of currency substitution, different trading institutions, and open market operations. We view the agenda of conducting monetary policy experiments in the lab as having the potential of becoming an additional tool for policymakers to isolate and analyze the interactions of different policy channels before implementing policies in the field.

# References


Aliprantis, Charalambos, Gabriele Camera, and Daniela Puzzello (2007). "Contagion Equilibria in a Monetary Model." *Econometrica*, 75, 277-282.

Anbarci, Nejat, Rirchard Dutu, and Nick Feltovich (2015). "Inflation Tax in the Lab: a Theoretical and Experimental Study of Competitive Search Equilibrium with Inflation." *Journal of Economic Dynamics and Control*, 61, 17-33.

Anderson, Richard, Michael Bordo, and John Duca (2015). "Money and Velocity During Financial Crises: From the Great Depression to the Great Recession." *Mimeo.*

Araujo, Luis, Braz Camargo, Raoul Minetti, and Daniela Puzzello (2012). "The Essentiality of Money in Environments with Centralized Trade." *Journal of Monetary Economics*, 59, 612-621.

Arifovic, Jasmina (1996). "The Behavior of the Exchange Rate in the Genetic Algorithm and Experimental Economies." *Journal of Political Economy*, 104, 510–541.

Aruoba, Boragan, Guillaume Rocheteau, and Christopher Waller (2007). "Bargaining and the Value of Money." *Journal of Monetary Economics*, 54, 2636-2655.

Aruoba, Boragan, Christopher Waller, and Randall Wright (2011). "Money and Capital." *Journal of Monetary Economics*, 21, 105-124.

Baeriswyl, Romain and Camille Cornand (2018). "The Distortionary Effect of Monetary Policy: Credit Expansion vs. Lump-sum Transfers in the Lab." *B.E. Journal of Macroeconomics*, 18, 1-30.

Bailey, Martin J. (1956). "The Welfare Cost of Inflationary Finance." *Journal of Political Economy*, 64, 93–110.

Berentsen, Aleksander, Guido Menzio, and Randall Wright. (2011). "Inflation and Unemployment in the Long Run." *American Economic Review*, 101, 371-98.

Berentsen, Aleksander, Michael McBride, and Guillaume Rocheteau (2017). "Limelight on Dark Markets: Theory and Experimental Evidence on Liquidity and Information." *Journal of Economic Dynamics and Control*, 5, 70-90.

Bernanke, Ben. (2020). "The New Tools of Monetary Policy." *American Economic Review*, 110, 943-983.

Bernasconi, Michele and Oliver Kirchkamp (2000). "Why do monetary policies matter? An experimental study of saving and inflation in an overlapping generations model." *Journal of Monetary Economics*, 46, 315–343.

Bethune, Zachary, Michael Choi, and Randall Wright (2019). "Frictional Goods Markets: Theory and Applications." *Review of Economic Studies*, forthcoming.

Bewley, Truman (1980). "The Optimum Quantity of Money." In *Models of Monetary Economies*, ed. by J. H. Kareken and Neil Wallace, 169–210.

Brown, Paul (1996). "Experimental Evidence on Money as a Medium of Exchange." *Journal of Economic Dynamics and Control*, 20, 583-600.

Bullard, James (2012). "The U.S. Monetary Outlook", speech 196, Federal Reserve Bank of St. Louis.

Burdett, Kenneth, Shouyong Shi, and Randall Wright (2001). "Pricing and Matching with Frictions." *Journal of Political Economy*, 109, 1060–1085.

Camera, Gabriele and Marco Casari (2014). "The Coordination Value of Monetary Exchange: Experimental Evidence." *American Economic Journal: Microeconomics*, 6, 629–660.

Camera, Gabriele, Charles Noussair, and Steven Tucker (2003). "Rate-of-return dominance and efficiency in an experimental economy." *Economic Theory*, 22, 629-660.

Chiu, Jonathan and Miguel Molico (2010). "Liquidity, Redistribution, and the Welfare Cost of Inflation." *Journal of Monetary Economics*, 57, 428-38.

Craig, Ben and Guillaume Rocheteau (2008). "Inflation and Welfare: A Search Approach." *Journal of Money, Credit and Banking*, vol 40, 89–119.

Davis, Douglas, Oleg Korenok, Peter Norman, Bruno Sultanum, and Randall Wright (2019). "Playing with Money." Working Paper.

Deck, Cary, Kevin McCabe, and David Porter (2006). "Why Stable Fiat Money Hyperinflates: Results from an Experimental Economy." *Journal of Economic Behavior and Organization*, 61, 471-486.

Diercks, Anthony M. (2019). "A Reader's Guide to Optimal Monetary Policy." Available at SSRN: https://ssrn.com/abstract=2989237 or http://dx.doi.org/10.2139/ssrn.2989237

Ding, Shuze and Daniela Puzzello (2020). "Legal Restrictions and International Currencies: An Experimental Approach."*Journal of International Economics*, forthcoming.

Duffy, John (2016). "Macroeconomics: A Survey of Laboratory Research." In *Macroe-*

*conomics: A Survey of Laboratory Research*, edited by Kagel, John H., and Alvin E. Roth, Princeton University Press.

Duffy, John, Janet Hua Jiang, and Huan Xie (2019), "Experimental Asset Markets with An Indefinite Horizon." Available at SSRN: https://ssrn.com/abstract=3420184.

Duffy, John and Jack Ochs (1999). "Emergence of Money as a Medium of Exchange: An Experimental Study." *American Economic Review*, 89: 847–877.

Duffy, John and Jack Ochs (2002). "Intrinsically Worthless Objects as Media of Exchange: Experimental Evidence." *International Economic Review*, 43, 637–673.

Duffy, John, Alexander Matros, and Ted Temzelides (2011). "Competitive Behavior in Market Games: Evidence and Theory." *Journal of Economic Theory*, 146, 1437-1463.

Duffy, John and Daniela Puzzello (2014*a*). "Gift Exchange versus Monetary Exchange: Experimental Evidence." *American Economic Review*, 104, 1735–1776.

Duffy, John, and Daniela Puzzello (2014*b*). "Experimental Evidence on the Essentiality and Neutrality of Money in a Search Model." *Experiments in Macroeconomics* vol 17, Binley, UK: Emerald Group Publishing Ltd.

Duffy, John, and Daniela Puzzello (2018). "The Friedman Rule in the Laboratory." *Mimeo*.

Eberly, Janice C., James H. Stock, and Jonathan H. Wright (2019). "The Federal Reserve's Current Framework for Monetary Policy: A Review and Assessment." National Bureau of Economic Research Working Paper 26002.

Fischbacher, Urs (2007). "Z-Tree: Toolbox for Ready-Made Economic Experiments." *Experimental Economics*, 10, 171–178.

Fréchette, Guillaume and Sevgi Yuksel (2017). "Infinitely repeated games in the laboratory: four perspectives on discounting and random termination." *Experimental Economics*, 20, 279-308.

Friedman, Milton and Anna Schwartz (1981). *Monetary Trends in the United States and United Kingdom: Their Relation to Income, Prices, and Interest Rates.* University of Chicago Press for the NBER.

Hommes, Cars (2020). "Behavioral and Experimental Macroeconomics and Policy Analysis: a Complex Systems Approach." *Journal of Economic Literature,* forthcoming.

Jiang, Janet Hua and Cathy Zhang (2018). "Competing Currencies in the Laboratory." *Journal of Economic Behavior and Organization*, 154, 253-280.

Jiang, Janet Hua, Daniela Puzzello, and Cathy Zhang (2020). "How Long is Forever in the Laboratory? Three Implementations of an Infinite-Horizon Monetary Economy" *Journal of Economic Behavior and Organization*, forthcoming.

Lagos, Ricardo (2010). "Asset Prices and Liquidity in an Exchange Economy." *Journal* *of Monetary Economics*, 57(8), 913-930.

Lagos, Ricardo and Randall Wright (2005). "A Unified Framework for Monetary Theory and Policy Analysis." *Journal of Political Economy*, 113, 463–486.

Lagos, Ricardo and Shengxing Zhang (2019). "The Limits of Onetary Economics: On Money as a Medium of Exchange in Near-Cashless Credit Economies." mimeo.

Lagos, Ricardo and Shengxing Zhang (2020*a*). "Turnover Liquidity and the Transmission of Monetary Policy." *American Economic Review*, 110, 1635-72.

Lagos, Ricardo and Shengxing Zhang (2020*b*). "The Limits of Onetary Economics: On Money as a Latent Medium of Exchange." mimeo.

Lian, Peng and Charles R. Plott (1998). "Markets, Macroeconomics and Money in a Laboratory Experimental Environment." *Economic Theory*, 12, 21-75.

Lim, Suk S., Edward C. Prescott, and Shyam Sunder (1994). "Stationary Solution to the Overlapping generations model of fiat money: experimental evidence." *Empirical Economics*, 19, 255-277.

Lucas, Robert E. (1980)."Two Illustrations of the Quantity Theory of Money." *American Economic Review*, 70, 1005-14.

Lucas, Robert E. (2000). "Inflation and Welfare." *Econometrica*, 68(2), 247–274.

Lucas, Robert E. and Juan Pablo Nicolini (2015). "On the Stability of Money Demand." *Journal of Monetary Economics*, 73, 48-65.

Marimon, Ramon and Shyam Sunder (1993). "Indeterminacy of Equilibria in a Hyper-inflationary World: Experimental Evidence." *Econometrica*, 61, 1073-107.

Marimon, Ramon and Shyam Sunder (1994). "Expectations and learning under alternative monetary regimes: an experimental approach." *Economic Theory*, 4, 131-162.

Marimon, Ramon and Shyam Sunder (1995). "Does a Constant Money Growth Rule Help Stabilize Inflation?: Experimental Evidence." GSIA Working Papers, Carnegie Mellon University, Tepper School of Business.

Molico, Miguel (2006). "The Distribution of Money and Prices in Search Equilibrium." *International Economic Review*, 47, 701–722.

Ragan, Christopher (1998), "On the Believable Benefits of Low Inflation." Bank of Canada Working Paper 98-15.

Rietz, Justin (2019). "Secondary Currency Acceptance: Experimental Evidence with a Dual Currency Search Model." *Journal of Economic Behavior and Organization*, 166, 403-431.

Rocheteau, Guillaume and Ed Nosal (2017). *Money, Payments and Liquidity*, MIT Press.

Rocheteau, Guillaume and Randall Wright (2005). "Money in search equilibrium, in competitive equilibrium, and in competitive search equilibrium." *Econometrica*, 73, 175-202.

Rolnick, Arthur J. and Warren E. Weber (1997). "Money, Inflation, and Output under Fiat and Commodity Standards." *Journal of Political Economy*, 105, 1308-321.

Roth, Alvin and Keith Murnighan (1978). "Equilibrium Behavior and Repeated Play of the Prisoner's Dilemma." *Journal of Mathematical Psychology*, 17, 189–198.

Shapley, Lloyd, and Martin Shubik (1977). "Trade Using One Commodity as a Means of Payment." *Journal of Political Economy*, 85, 937-968.

Shi, Shouyong (1997). "A Divisible Search Model of Fiat Money." *Econometrica*, 65(1), 75-102.

Stockman, Alan (1981). "Anticipated inflation and the capital stock in a cash in-advance economy." *Journal of Monetary Economics*, 8, 387-393.

Townsend, Robert (1980). "Models of Money with Spatially Separated Agents." In *Models of Monetary Economies*, ed. by J. H. Kareken and Neil Wallace, 265–304.

# Appendix A Additional Tables

In this appendix we report additional analysis and findings.

## A.1 Output in Market B

Figure A.1 graphs the average output per period in market B, with 95% confidence intervals. Tables A.1 examines the treatment effect on average market B output relative to the CM treatment. Table A.2 reports pairwise comparisons between treatments. Table A.3 reports the time trend of average market B output.

Average output in market B is broadly consistent with the directional hypotheses based on theoretical predictions, e.g., output in market B is significantly lower in GS-15, GS-30 and LS-30 than in CM and PR-30. However, there is one exception as output in GS-30 is not significantly lower than output in GS-15.

Perhaps not surprisingly, point predictions are not fully supported by the data. Market B average output in the CM and PR-30 (neutral) treatments tends to be slightly lower than the theoretical prediction, while output in GS-30 tends to be higher than predicted. Specifically, average output levels in CM and PR-30 are equal to 8.69 and 8.60, and significantly lower than the theoretical prediction of 10. Average output in GS-30 is equal to 7.60, which is significantly higher than the theoretical prediction of 6.5. Average output in GS-15 is equal to 7.56 which is not significantly different from 7.95. Similarly average output in LS-30 at 6.55 is very close and not significantly different from the theoretical prediction of 6.5.

There is no significant time trend except for PR-30, which exhibited a downward trend (the downward trend in PR-30 may help to explain its relatively higher market B inflation relative to GS-30 and LS-30).

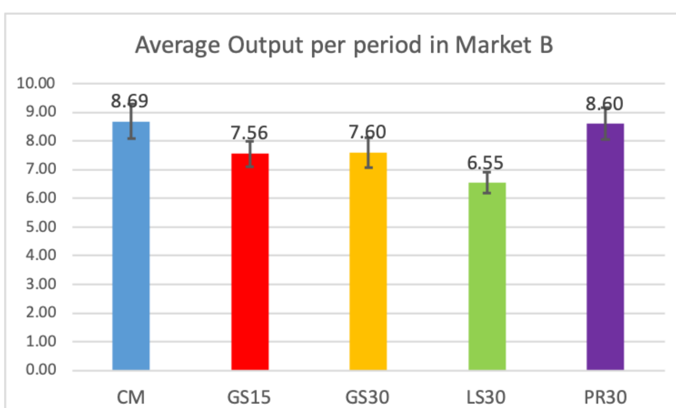


Figure A.1: Average Market B Output

Notes. Theory predicts output in market B is 10 in CM and PR-30, 7.95 in GS-15, and 6.5 in GS-30 and LS-30.

Table A.1: Regression of Average B Output on Treatment Dummies

| Variables | Avg. Market B Output |
|---|---|
| GS-15 | $-1.124^{***}$ |
| | (0.375) |
| GS-30 | $-1.088^{***}$ |
| | (0.397) |
| LS-30 | $-2.142^{***}$ |
| | (0.352) |
| PR-30 | -0.086 |
| | (0.412) |
| Constant | $8.688^{***}$ |
| | (0.301) |
| Observations | 623 |
| R-squared | 0.069 |

Notes.
(1) Robust standard errors in parentheses.
(2) * p-value < 0.10, ** p-value < 0.05, *** p-value < 0.01.

Table A.2: Estimated Difference in Average Market B Output

| | GS-30 | LS-30 | PR-30 |
|---|---|---|---|
| GS-15 | 0.036 | $-1.019^{***}$ | $1.038^{***}$ |
| | (0.3418) | (0.2890) | (0.3594) |
| GS-30 | | $-1.055^{***}$ | $1.002^{***}$ |
| | | (0.3163) | (0.3817) |
| LS-30 | | | $2.056^{***}$ |
| | | | (0.3352) |

Notes.
(1) Robust standard errors in parentheses.
(2) * p-value < 0.10, ** p-value < 0.05, *** p-value < 0.01.

Table A.3: Time Trend in Average Market B Output

| | Obs. | Coef. | Robust Std. Err. |
|---|---|---|---|
| CM | 134 | -0.091 | 0.095 |
| GS-15 | 129 | -0.007 | 0.062 |
| GS-30 | 134 | 0.039 | 0.071 |
| LS-30 | 118 | 0.062 | 0.056 |
| PR-30 | 108 | -0.197** | 0.083 |

Notes.
(1) The dependent variable is average market B output, and the regressors are period and the constant. We report only the coefficient for period.
(2) * p-value < 0.10, ** p-value < 0.05, *** p-value < 0.01.

## A.2 Inflation by Session

Table A.4 reports more details on inflation rates by session. Specifically, column 3 and column 6 report the estimated inflation rates by session, for market A and market B, respectively. The other columns report deviations of inflation rates from point predictions. For example, columns 4 and 5 show that in two out of four sessions of the CM treatment, inflation rates in Market A were higher than predicted; all sessions of the GS-30 treatment exhibited lower inflation in Market A than predicted, etc.

Table A.4: Estimated Inflation and Deviations from Theoretical Point Predictions

| | | Market A | | | | Market B | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Deviation from ss | | | | Deviation from ss | | |
| | Obs. | Estimated Inflation | Estimate | | robust std. err. | Estimated Inflation | Estimate | | robust std. err. |
| CM1 | 25 | 0.004 | 0.004 | | 0.010 | -0.005 | -0.005 | | 0.012 |
| CM2 | 46 | 0.044 | 0.044 | *** | 0.014 | 0.077 | 0.077 | *** | 0.012 |
| CM3 | 33 | 0.025 | 0.025 | | 0.019 | 0.029 | 0.029 | ** | 0.013 |
| CM4 | 30 | 0.045 | 0.045 | * | 0.025 | 0.049 | 0.049 | | 0.033 |
| **CM-All** | **134** | **0.035** | **0.035** | *** | **0.012** | **0.047** | **0.047** | *** | **0.015** |
| GS15-1 | 25 | 0.154 | 0.004 | | 0.010 | 0.153 | 0.003 | | 0.010 |
| GS15-2 | 30 | 0.169 | 0.019 | | 0.020 | 0.140 | -0.01 | | 0.024 |
| GS15-3 | 44 | 0.105 | -0.045 | ** | 0.018 | 0.135 | -0.015 | | 0.014 |
| GS15-4 | 30 | 0.123 | -0.027 | | 0.022 | 0.241 | 0.091 | ** | 0.036 |
| **GS15-All** | **129** | **0.132** | **-0.018** | ** | **0.009** | **0.156** | **0.006** | | **0.011** |
| GS30-1 | 25 | 0.242 | -0.058 | *** | 0.020 | 0.248 | -0.052 | *** | 0.009 |
| GS30-2 | 46 | 0.254 | -0.046 | *** | 0.012 | 0.267 | -0.033 | ** | 0.014 |
| GS30-3 | 23 | 0.246 | -0.054 | ** | 0.021 | 0.269 | -0.031 | * | 0.017 |
| GS30-4 | 40 | 0.230 | -0.070 | *** | 0.023 | 0.247 | -0.053 | * | 0.027 |
| **GS30-All** | **134** | **0.241** | **-0.059** | *** | **0.010** | **0.252** | **-0.048** | *** | **0.010** |
| LS30-1 | 25 | 0.267 | -0.033 | ** | 0.015 | 0.256 | -0.044 | ** | 0.018 |
| LS30-2 | 30 | 0.169 | -0.131 | *** | 0.013 | 0.218 | -0.082 | *** | 0.024 |
| LS30-3 | 33 | 0.183 | -0.117 | *** | 0.021 | 0.221 | -0.079 | *** | 0.016 |
| LS30-4 | 30 | 0.242 | -0.058 | * | 0.034 | 0.336 | 0.036 | | 0.036 |
| **LS30-All** | **118** | **0.207** | **-0.093** | *** | **0.015** | **0.242** | **-0.058** | *** | **0.013** |
| PR30-1 | 25 | 0.197 | -0.103 | *** | 0.013 | 0.253 | -0.047 | *** | 0.016 |
| PR30-2 | 30 | 0.200 | -0.010 | *** | 0.022 | 0.282 | -0.018 | | 0.041 |
| PR30-3 | 23 | 0.225 | -0.075 | *** | 0.017 | 0.263 | -0.037 | | 0.030 |
| PR30-4 | 30 | 0.281 | -0.019 | | 0.018 | 0.291 | -0.009 | | 0.019 |
| **PR30-All** | **108** | **0.225** | **-0.075** | *** | **0.010** | **0.276** | **-0.024** | * | **0.013** |

Notes.
(1) Inflation is estimated from regressing ln(Price) on Period with robust standard errors.
(2) * p-value < 0.10, ** p-value < 0.05, *** p-value < 0.01.

## A.3 Average Market A Output by Session

Table A.5 reports more details on average output produced in Market A as well as deviations from point predictions, by session. For example, it shows that average output in Market A was higher than predicted in three of the four sessions of the GS-30 treatment. Results for other treatments and sessions can be read similarly.

Table A.5: Average Market A Output and Deviations from Theoretical Point Predictions

| Session | Obs. | Ave. Output A | Ave. Output A -SS | | |
|---|---|---|---|---|---|
| | | | Estimate | | Robust Std. Err. |
| CM-1 | 25 | 12.711 | 2.711 | *** | 0.506 |
| CM-2 | 46 | 7.484 | -2.516 | *** | 0.476 |
| CM-3 | 33 | 11.594 | 1.594 | *** | 0.528 |
| CM-4 | 30 | 8.950 | -1.050 | ** | 0.391 |
| **CM-All** | **134** | **9.800** | **-0.200** | | **0.303** |
| GS15-1 | 25 | 7.432 | 0.519 | | 0.365 |
| GS15-2 | 30 | 8.561 | 1.649 | *** | 0.377 |
| GS15-3 | 44 | 8.108 | 1.195 | *** | 0.308 |
| GS15-4 | 30 | 6.064 | -0.848 | ** | 0.352 |
| **GS15-All** | **129** | **7.607** | **0.694** | *** | **0.191** |
| GS30-1 | 25 | 8.956 | 3.956 | *** | 0.559 |
| GS30-2 | 46 | 6.701 | 1.701 | *** | 0.317 |
| GS30-3 | 23 | 7.245 | 2.245 | *** | 0.422 |
| GS30-4 | 40 | 4.218 | -0.782 | ** | 0.360 |
| **GS30-All** | **134** | **6.474** | **1.474** | *** | **0.244** |
| LS30-1 | 25 | 8.123 | 3.122 | *** | 0.369 |
| LS30-2 | 30 | 4.436 | -0.564 | *** | 0.200 |
| LS30-4 | 33 | 8.598 | 3.598 | *** | 0.439 |
| LS30-4 | 30 | 8.763 | 3.763 | *** | 0.493 |
| **LS30-All** | **118** | **7.481** | **2.481** | | **0.257** |
| PR30-1 | 25 | 10.317 | 0.317 | | 0.443 |
| PR30-2 | 30 | 11.779 | 1.779 | *** | 0.353 |
| PR30-3 | 23 | 8.869 | -1.131 | ** | 0.444 |
| PR30-4 | 30 | 10.006 | 0.006 | | 0.378 |
| **PR30-All** | **108** | **10.329** | **0.329** | | **0.221** |

Notes.
(1)* p-value < 0.10, ** p-value < 0.05, *** p-value < 0.01.
(2) Steady state market A output is 10 in treatments CM and PR-30, 6.9126 in treatment GS-15, and 5 in treatments GS-30 and LS-30.

## A.4 Welfare Ratio by Session

Table A.6 reports more details on average period welfare, as well as deviations from the theoretical point predictions, by session. The table shows that welfare is lower than predicted in most sessions.

Table A.6: Welfare Ratio and Deviations from Theoretical Point Predictions

| Session | Obs. | Welfare Ratio | Welfare Ratio - Steady State Estimate | | Robust Std. Err | Welfare Ratio at Avg. Output |
|---|---|---|---|---|---|---|
| CM-1 | 25 | 0.898 | -0.081 | *** | 0.008 | 1.000 |
| CM-2 | 46 | 0.731 | -0.248 | *** | 0.015 | 0.926 |
| CM-3 | 33 | 0.887 | -0.093 | *** | 0.011 | 0.995 |
| CM-4 | 30 | 0.850 | -0.129 | *** | 0.013 | 0.962 |
| **CM-All** | **134** | **0.827** | **-0.152** | *** | **0.009** | **0.976** |
| GS15-1 | 25 | 0.777 | -0.131 | *** | 0.018 | 0.924 |
| GS15-2 | 30 | 0.861 | -0.046 | *** | 0.012 | 0.954 |
| GS15-3 | 44 | 0.757 | -0.151 | *** | 0.009 | 0.943 |
| GS15-4 | 30 | 0.768 | -0.140 | *** | 0.015 | 0.875 |
| **GS15-All** | **129** | **0.787** | **-0.120** | *** | **0.007** | **0.929** |
| GS30-1 | 25 | 0.808 | -0.015 | | 0.016 | 0.962 |
| GS30-2 | 46 | 0.804 | -0.018 | * | 0.010 | 0.900 |
| GS30-3 | 23 | 0.797 | -0.026 | | 0.017 | 0.918 |
| GS30-4 | 40 | 0.675 | -0.148 | *** | 0.02 | 0.775 |
| **GS30-All** | **134** | **0.765** | **-0.058** | *** | **0.009** | **0.891** |
| LS30-1 | 25 | 0.845 | 0.022 | | 0.020 | 0.943 |
| LS30-2 | 30 | 0.680 | -0.143 | *** | 0.010 | 0.789 |
| LS30-4 | 33 | 0.861 | 0.038 | *** | 0.012 | 0.954 |
| LS30-4 | 30 | 0.844 | 0.021 | | 0.015 | 0.958 |
| **LS30-All** | **118** | **0.807** | **-0.016** | | **0.010** | **0.926** |
| PR30-1 | 25 | 0.872 | -0.108 | *** | 0.016 | 0.983 |
| PR30-2 | 30 | 0.825 | -0.154 | *** | 0.017 | 0.996 |
| PR30-3 | 23 | 0.776 | -0.204 | *** | 0.018 | 0.960 |
| PR30-4 | 30 | 0.876 | -0.104 | *** | 0.017 | 0.979 |
| **PR30-All** | **108** | **0.839** | **-0.140** | *** | **0.009** | **0.984** |

Notes.
(1)* p-value < 0.10, ** p-value < 0.05, *** p-value < 0.01.
(2) The steady state welfare ratio is 0.979 for CM and PR-30, 0.907 for GS-15, and 0.823 for GS-30 and LS-30.

## A.5 Spending Ratio and Fraction of Money Held by Buyers

The regression in Table A.7 shows there are no significant treatment effects on the fraction of money holdings subjects spent in the inflationary treatments relative to the CM treatment; this is consistent with the theoretical predictions. However, point predictions are not supported as subjects tended not to spend all their money holdings. Similar results are observed in Duffy and Puzzello (2014ab, 2018), and could be attributed to some precautionary motive and uncertainty in the price realization.

Table A.7: Regression of Individual Token Spending Ratio on Treatment Dummies

| Variables | Market A Spending Ratio | Market B Spending Ratio |
|---|---|---|
| GS-15 | 0.029 | 0.055 |
| | (0.056) | (0.048) |
| GS-30 | 0.091 | -0.045 |
| | (0.062) | (0.065) |
| LS-30 | -0.081 | -0.027 |
| | (0.058) | (0.057) |
| PR-30 | 0.048 | -0.014 |
| | (0.057) | (0.056) |
| Constant | $0.716^{***}$ | $0.754^{***}$ |
| | (0.043) | (0.038) |
| Observations | 3,074 | 3,073 |
| R-squared | 0.047 | 0.015 |

Notes.
(1) Standard errors are clustered at the subject level.
(2) * p-value < 0.10, ** p-value < 0.05, *** p-value < 0.01.
(3) Note that some subjects enter the market with a zero token balance; we omit those observations in the regression.

Table A.8 shows the time trend in the individual buyer's spending ratio by regressing the fraction of money spent out of the buyer's money holding in each market on time period and the constant. There is no significant time trend in the individual spending ratio except for market B of treatment CM (which exhibited a positive trend) and treatment PR (which exhibited a negative trend).

Table A.9 shows the time trend of the fraction of money held by buyers out of the total money supply. It shows that in all inflationary treatments, the fraction of money held by buyers in market A tended to decrease over time, which implies that in the aggregate there is less money available to be spent. This may have contributed to the observation of lower inflation rates than predicted in these treatments. Also, note that this effect is weaker in the GS-30 relative to LS-30 and PR-30 as indicated by the smaller magnitude of the coefficient: this is because robot buyers always have a spending ratio of 1, which dampens the time variation in the fraction of money held by (human) buyers in market A. This may help to explain why market A inflation tended to be higher in the GS-30 treatment than in the LS-30 and PR-30 treatments.

Table A.8: Time Trend in Individual Spending Ratio

| | Market A | | | Market B | | |
|---|---|---|---|---|---|---|
| | Obs. | Coef. | Std. Err. | Obs. | Coef. | Std. Err. |
| CM | 629 | 0.0052 | 0.0058 | 645 | 0.0085** | 0.0037 |
| GS-15 | 645 | 0.0039 | 0.0032 | 633 | 0.0060 | 0.0035 |
| GS-30 | 670 | -0.0013 | 0.0042 | 670 | 0.0005 | 0.0054 |
| LS-30 | 590 | -0.0026 | 0.0051 | 590 | -0.0008 | 0.0055 |
| PR-30 | 540 | 0.0020 | 0.0045 | 535 | -0.0129** | 0.0052 |

Notes.
(1) The dependent variable is individual spending ratio, and the regressands are period and the constant. We report the coefficient for period.
(2) Standard errors are clustered at the subject level.
(3) * p-value < 0.10, ** p-value < 0.05, *** p-value < 0.01.

Table A.9: Time Trend in Fraction of Money Held by Buyers

| | | Market A | | Market B | |
|---|---|---|---|---|---|
| | Obs. | Coef. | Robust Std. Err. | Coef. | Robust Std. Err. |
| CM | 134 | -0.0049 | 0.0031 | 0.0080** | 0.0036 |
| GS-15 | 129 | -0.0060*** | 0.0023 | 0.0064*** | 0.0024 |
| GS-30 | 134 | -0.0067* | 0.0038 | -0.0024 | 0.0018 |
| LS-30 | 118 | -0.0140*** | 0.0040 | -0.0010 | 0.0038 |
| PR-30 | 108 | -0.0210*** | 0.0038 | 0.0076*** | 0.0027 |

Notes.
(1) Fraction of Money Held by Buyers is defined as the sum of money holdings by all (human and robot) buyers to the total amount of money supply before the market opens.
(2) The regressors are period and constant, and we report the coefficient on period and robust standard errors.
(3) * p-value < 0.10, ** p-value < 0.05, *** p-value < 0.01.

# Appendix B Time Paths of Average Market A Output and Price Levels

Figures B.1 and B.2 show the time paths for average Market A output and price levels, for each session of each treatment.

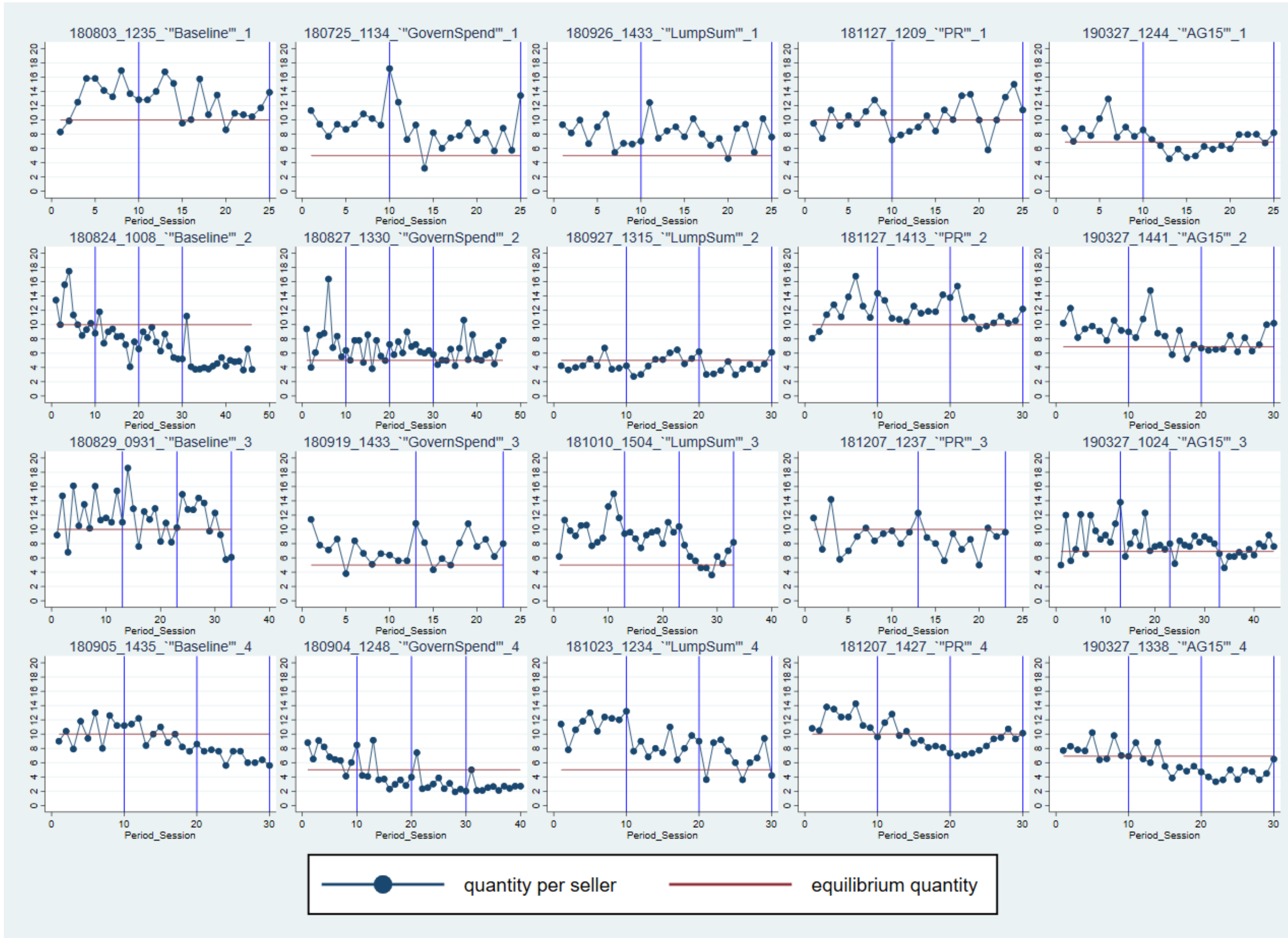


Figure B.1: Output in Market A by Session

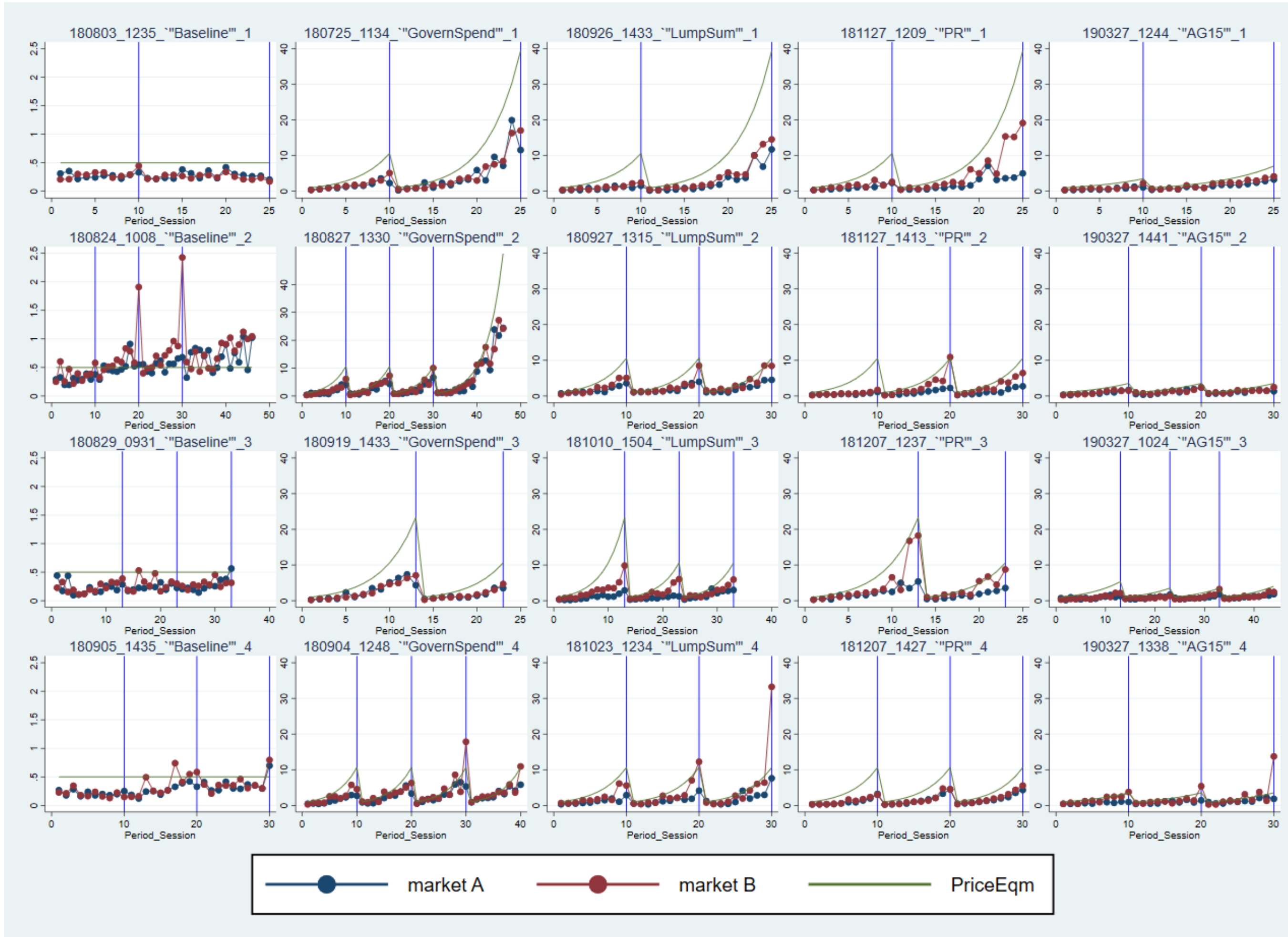


Figure B.2: Price Level in Market A and Market B by Session