

# **Inflation tax in the lab: a theoretical and experimental study of competitive search equilibrium with inflation**

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## **Abstract**

In this paper we measure the effect of the inflation tax on economic activity and welfare within a controlled setting. To do so, we develop a model of price posting and monetary exchange with inflation and finite populations. The model, which provides a game-theoretic foundation to Rocheteau and Wright (2005)'s competitive search monetary equilibrium, is used to derive theoretical propositions regarding the effects of inflation in this environment, which we test with a laboratory experiment that closely implements the theoretical framework. We find that the inflation tax is harmful – with cash holdings, production and welfare all falling as inflation rises – and that its effect is relatively larger at low inflation rates than at higher rates. For instance, for inflation rates between 0% to 5%, welfare in the two markets we consider (2[seller]x2[buyer] and 3x2) falls by roughly 1 percent for each percentage-point rise in inflation, compared with 0.4 percent over the range from 5% to 30%. Our findings lead us to conclude that the impact of the inflation tax should not be underestimated, even under low inflation.

**Keywords:** money; inflation tax; directed search; posted price; cash balance; welfare loss; friction; experiment.

*Journal of Economic Literature* classifications: E31, E40, C90.

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# 1 Introduction

When prices rise, the real value of individuals' money holdings falls. This phenomenon is known as the *inflation tax*. It affects agents' behaviour, inducing them to adopt strategies (such as shifting consumption away from cash-intensive activities, or simply holding less money) to avoid its effects. Both the inflation tax itself and the resulting behavioural distortions can have implications for social welfare. This inflation tax channel is present in many monetary models, from reduced-form cash-in-advance models (Lucas and Stokey, 1987) to the more micro-founded money search models (Lagos and Wright, 2005).

Quantifying the effect of the inflation tax is tricky, however. The inflation tax may be one of several channels for inflation, making it difficult to disentangle each within the broader issue of the costs of inflation (Burstein and Hellwig, 2008). Moreover, the welfare loss due to inflation may not be due to the tax itself but to other frictions such as an inefficient pricing mechanism, as the welfare costs of inflation have been shown to depend critically on the pricing mechanism being used (Aruoba et al, 2007; Craig and Rocheteau, 2008; Rocheteau, 2012). Also, due to the inherent difficulty of implementing a controlled test of the inflation tax in the field, all measures of the effects of inflation – regardless of the channel – have been conducted within the confines of theoretical macroeconomic models.

In this paper we propose the first experimental measure of the inflation tax. Our goal is to help quantify the effect of the inflation tax using tools other than a theoretical construct. To do so, we begin by developing a simple model of monetary exchange with price posting suitable for experimental testing. The model is built by fitting the  $m$ -seller  $n$ -buyer ( $mxn$ ) price-posting model analysed by Burdett, Shi and Wright (2001), BSW hereafter, into the money search environment in the vein of Lagos and Wright (2005). We use the model to derive predictions relating to the effect of inflation on price-setting decisions by sellers, cash-holding decisions by buyers, production and welfare. We then test the model's predictions by conducting a laboratory experiment that closely implements the model's strategic setting. In our experiment, 193 subjects participated in a total of 2322 trading rounds, by taking on the role of buyers and sellers in one of two types of price-posting market (2x2 or 3x2), and making their decisions in an environment where the inflation rate is 0%, 5% or 30%.

Our results provide support for and help quantify the inflation tax, with behaviour in the experiment qualitatively in line with the theoretical predictions. Additionally, some striking quantitative results emerge. First, statistical tests easily reject the null hypothesis of no difference across our three inflation rates, showing that *the inflation tax matters*. Second, *the effect of the inflation tax is powerful*. In the 2x2 market, for example, real prices fall by 11.3 percent and welfare falls by 4.2 percent as inflation rises from 0% to 5%, and by a further 11.5 percent and 13.6 percent respectively when inflation jumps from 5% to 30%. Third, *a rise in inflation is relatively more consequential when initial inflation is low*. As inflation rises from 5% to 30% in the 2x2 market, each one-point increase in the inflation rate translates into a 0.5 percent drop in the real transaction price and a 0.4 percent drop in welfare. But when inflation rises from 0% to 5% we find that for each percentage-point increase in inflation, real transaction prices fall by 2.6 percent and welfare falls by 0.8 percent, an effect 2 to 5 times stronger. Similar results are observed in the 3x2 market.

Using a controlled setting, our approach also allows us to provide novel insights about the effect of the inflation tax that, while tangential to our main research questions, may help guide future research. First, we can precisely track the effects of changing parameters in the experiment. For instance, how does a change in market size or tightness impact on buyers' visit and cash holding strategies? What is their effect on sellers' price posting strategies? How do those reactions compare to those predicted by the model? Second, we are able to assess and quantify out-of-

equilibrium behaviour, such as dispersion in prices and cash holdings as well as agents' time spent making their decisions.

In the end, our research points to a significant effect of the inflation tax on real economic activity, perhaps greater than one may have expected, and apparent even – indeed, especially – when inflation is low. We view our findings as a reminder that the inflation tax should not be underestimated, even under low inflation.

## 2 Other relevant work

Although there is a huge literature concerned with inflation, we will focus on a handful of papers most closely related to ours, with emphasis on papers not mentioned in the introduction. Much of the work on the effects of inflation has been conducted within theoretical macroeconomic models. This work has been very useful – for instance, in quantifying the costs of inflation to the economy. The earliest attempts by Bailey (1956) and Friedman (1969) treated real money balances as a consumption good and inflation as a tax on these balances, leading to a deadweight loss like that of an excise tax on a commodity. Following Lucas (1987), compensated measures of the costs of inflation within a general equilibrium setting (based on the increase in consumption that an individual would require to be as well off as under zero inflation) were computed, such as Cooley and Hansen (1989) using a cash-in-advance model or Lucas (2000) including money as an argument in the utility function. The welfare cost of 10% inflation was found to be as high as one percent of GDP.

Recently, Burstein and Hellwig (2008) developed a model combining nominal rigidities and the inflation tax. They found that the welfare cost of raising inflation from 2.2% to 12.2% varies widely by model parameters, from roughly zero to almost 7 percent of GDP. More importantly, and directly related to our findings, they showed that the contribution of relative price distortions to the welfare effect of inflation is negligible compared the other channel: the inflation tax (or more precisely, the opportunity cost of holding money since in addition to inflation their model also has a positive real interest rate).

Using short-cuts such as cash-in-advance constraints to introduce money, however, makes it difficult to source the effect of inflation on agents' decisions. As noted by Lucas (2000), “[these models] are not adequate to let us see how people would manage their cash holdings at very low interest rates. Perhaps for this purpose theories that take us farther on the search for foundations, such as the matching models introduced by Kiyotaki and Wright (1989), are needed” (p. 272). Since then, several papers have studied the costs of inflation using money search theory (e.g., Lagos and Wright, 2005; Craig and Rocheteau, 2011). They found that eliminating a 10% inflation rate can have a fairly large welfare benefit – as much as 4 percent of consumption in some circumstances. Other contributions have shown that the actual cost depends critically on the pricing mechanism used. In particular, by removing the holdup problem, mechanisms that include posting or competitive pricing instead of bargaining tend to find lower costs of inflation. For instance, with price posting, the cost of inflation is close to previous estimates in the non-search literature, around 1 percent (Craig and Rocheteau, 2008; Rocheteau and Wright, 2009; Rocheteau, 2012).

Molico (2006) considers a search-theoretic model of monetary exchange in which individuals bargain over both the amount of money and the quantity of goods in a decentralised market only. He uses numerical methods to characterise equilibria. He shows that changes in the money supply have no real effects if proportional transfers are used. With fixed lump-sum transfers of money, on the other hand, for low rates of inflation, an increase of the rate of monetary expansion tends to decrease the dispersion of money and prices and to improve welfare; when inflation is high enough, however, the opposite effects can occur.

While clarifying the theoretical effect of inflation on individual behaviour, none of the papers mentioned above

has attempted controlled testing of the qualitative and quantitative implications of their models. Laboratory experiments can serve as a useful complement to theory and to empirical studies using observational data from the field, owing to advantages such as precise control over the decision making environment (e.g., corresponding more closely to a theoretical model than the real world does), exogenous manipulation of key parameters such as the inflation rate (reducing issues such as endogeneity and selection), and accurate measurement of important variables. Macroeconomics was long considered beyond the reach of experimental methods, but the rise of micro foundations in macro models has made experiments increasingly feasible.<sup>1</sup> Studies of inflation are among the oldest examples of macroeconomics experiments (Marimon and Sunder, 1993, 1994, 1995; Lim, Prescott and Sunder, 1994; Bernasconi and Kirchkamp, 2000), but these experiments focused on hyperinflation while our interest is in moderate inflation levels. Money search – one component of our model – has been studied in the lab, by Brown (1996) and Duffy and Ochs (1999, 2002), and more recently Camera and Casari (2014) and Duffy and Puzzello (2014). Those papers concentrated on testing some of the fundamental implications of money–search theory, such as the acceptance of fiat money or the multiplicity of equilibria, rather than examining inflation specifically. Also, Kryvtsov and Petersen (2015) use an experimental dynamic stochastic general equilibrium (DSGE) model to examine another channel of monetary policy: expectations of future macroeconomic variables.

Although our experiment is arguably more about the short–run than long–run effect of the inflation tax, another relevant basis for comparison is the large empirical macro literature on the long–run consequences of inflation (e.g., Levine and Renelt, 1992; Bullard and Keating, 1995; Ahmed and Rogers, 2000; Rapach, 2003). Its conclusions are quite mixed, however, and seem to depend heavily on the average inflation rate in the past and also the econometric methodology used. For instance, McCandless and Weber’s (1995) cross–country study suggests no correlation at all between inflation and the growth rate of real output, while Barro (1995, 1996) report a negative correlation using a similar approach. Other studies have found threshold effects, with a small positive effect of inflation on real output that later dissipates for higher inflation rates (Bullard and Keating, 1995). (See also Bullard (1999) for a survey.) That field data do not provide much guidance on the issue may not come as a surprise, due to the inherent difficulty if implementing a controlled test of the inflation tax in the field. This highlights the relevance of our experimental approach where we can control the inflation tax and isolate its effects.

### 3 The model

Our model starts with the directed–search environment from Burdett, Shi and Wright (2001). (See also Julien, Kennes and King, 2000.) There are  $n \geq 2$  buyers and  $m \geq 2$  sellers. Sellers produce a homogeneous good, with cost of production 0 for the first unit, and production beyond the first unit impossible. Buyers are also identical, each with valuation  $Q > 0$  for the first unit and zero for any additional unit.<sup>2</sup>

Sellers compete in prices in order to attract buyers. Each seller simultaneously posts a price, which is observed by all buyers. Buyers then simultaneously make their visit choices; each can visit only one seller. Trade takes place at the seller’s posted price; if multiple buyers visit the same seller, one is randomly chosen to be able to buy. Buyers who aren’t chosen, and sellers who aren’t visited, do not trade.

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<sup>1</sup>See Duffy (2014) for a detailed survey of experimental macroeconomics, and in particular his section on monetary economics.

<sup>2</sup>In the experiment, we will set specific values for these parameters, but we keep our notation general for now.

### 3.1 BSW with money

To make the BSW model monetary, we fit it into the money search literature in the vein of Lagos and Wright (2005). As in those models, we divide each trading period into two sub-periods. In the first sub-period buyers and sellers participate in a centralised Walrasian market where they can produce and consume any quantity of a single, homogeneous consumption good, called the *general good*. Then they enter a second, decentralised market where they can trade a second good, called the *search good*. Both goods are perishable. As usual in these kinds of model, sellers use the Walrasian market to spend any money earned during the previous sub-period of decentralised trading, while buyers use it to acquire the cash they will need for the decentralised market in the upcoming sub-period. In contrast to Lagos and Wright (2005) who use random matching and bargaining, but similar to Rocheteau and Wright (2005), the Walrasian market is additionally used by our sellers to post prices for the decentralised market, and by each of our buyers to decide which seller to visit in that market. To that extent our model corresponds to a finite-population version of the competitive search monetary equilibrium in Rocheteau and Wright (2005) or Lagos and Rocheteau (2005).<sup>3</sup>

Money comes in the form of a perfectly divisible and storable object whose value relies on its use as a medium of exchange. It is available in quantity  $Z_t$  at time  $t$ , and can be stored in any non-negative quantity  $z_t$  by any agent. (Thus  $z_t$  is an agent's *nominal* cash balance at time  $t$ .) New money is injected or withdrawn via lump-sum transfers by the central bank in the centralised market at rate  $\tau$  such that  $Z_{t+1} = (1 + \tau)Z_t$ . Only buyers receive the transfer. Inflation is forecasted perfectly and both the quantity theory and the Fisher equation apply: if the money supply increases at rate  $\tau$ , so do prices and the nominal interest rate. We denote  $r$  the real interest rate and  $\beta$  the discount factor between the centralised market and the decentralised market; note that except for this discounting between sub-periods, there is no other discounting (e.g., there is not a further discounting between the second sub-period of time  $t$  and the first sub-period of time  $t + 1$ ). Since  $\beta = \frac{1}{1+r}$ , the nominal interest rate is  $i = \frac{1-\beta+\tau}{\beta}$  (from  $(1 + i) = (1 + r)(1 + \tau)$ ). In the experiment we will assume that the real interest rate is close to but strictly larger than zero, so that  $\beta$  is close to but strictly less than one. Thus  $\tau \approx i$ , so shifts in the nominal interest rate simply reflect changes in expected (and actual) inflation. The price of the general good is normalised to 1 and the clearing price of money in terms of the general good is denoted  $\phi_t$  (i.e., 1 unit of the general good costs  $1/\phi_t$  units of money).

Trade in the search good takes place as diagrammed in Figure 1. Sellers simultaneously post prices for the search good during the centralised market. Buyers observe all prices, then simultaneously choose (1) which seller to visit and (2) how much cash to carry. Buyers and sellers then proceed to the decentralised market where sellers are committed to their price and buyers are constrained by their money holdings. In particular the buyer is only able to buy if he is carrying enough cash to cover the posted price; we define a *serious buyer* as one satisfying this condition. Carrying cash is costly due to the inflation tax, as we will see below.

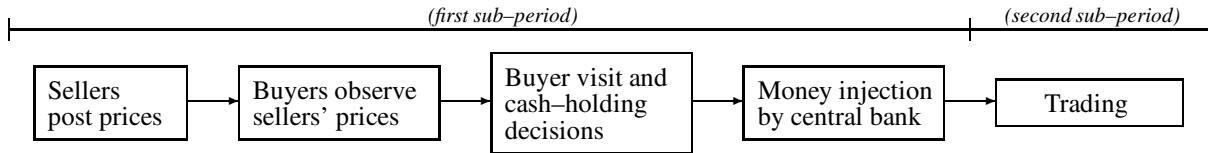
If a seller is visited by exactly one serious buyer, then they trade at the posted price. If a seller is visited by two or more serious buyers, then one is randomly chosen (with equal probability) to buy at the posted price. A seller visited by no serious buyers is unable to sell.<sup>4</sup>

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<sup>3</sup>Rocheteau and Wright (2005) and Lagos and Rocheteau (2005) make several important theoretical points, but those models would be quite difficult to implement in an experiment due to the assumption of continua of buyers and sellers. Our model, on the other hand, uses finite numbers of buyers and sellers, making experiments feasible. This feature additionally allows the buyer-seller matching to emerge from their individual decisions, rather than requiring an exogenous matching function. Other papers introducing price posting in money search models are Kultti and Riipinen (2003) and Julien, Kennes and King (2008). Both papers assume that goods are divisible but money is indivisible, which makes them ill-suited for studying inflation. See also Corbae, Temzelides and Wright (2003) for a model of directed matching, also with indivisible money, and with prices determined by bargaining.

<sup>4</sup>We assume that the seller does not change her price in response to the number of buyers visiting her. This is in keeping with Burdett, Shi

Figure 1: Sequence of decisions associated with the decentralised market



### 3.2 Buyer and seller value functions

Buyers have the instantaneous utility function  $U_t^b = x_t + \beta u(q_t)$ , where  $x_t$  is net consumption of the general good at time  $t$ ,  $u(q_t)$  is the utility from consuming  $q_t$  units of the search good (with  $u(0) = 0$  and  $u(q_t) = Q$  for  $q_t \geq 1$ ), and  $\beta \in [0, 1]$  is the discount factor between the centralised and decentralised market. Sellers' instantaneous utility function is  $U_t^s = x_t - \beta c(q_t)$ , where  $c(q_t)$  is the cost of producing  $q_t$  units of the search good (with  $c(0) = c(1) = 0$  and  $c(q_t) = +\infty$  for  $q_t > 1$ ).

Let  $W^b(z)$  and  $V^b(z)$  be the value functions for a buyer holding  $z$  units of money in the centralised and frictional markets, respectively. If a buyer decides to take part in the decentralised market we have:

$$W^b(z) = \max_{x, \hat{z}} \left\{ x + \beta V^b(\hat{z}) \right\}, \quad \text{subject to} \quad \phi \hat{z} + x = \phi(z + T). \quad (1)$$

When choosing  $x$  (the net consumption of the general good) and a quantity of money to bring to the frictional market,  $\hat{z}$ , buyers take into account that the combined real value (i.e., measured in terms of the general good) of these two quantities must equal the sum of the money they brought to the Walrasian market,  $\phi z$ , and the amount received from the central bank,  $\phi T$ . Substituting out  $x$  yields

$$W^b(z) = \phi(z + T) + \max_{\hat{z}} \left\{ -\phi \hat{z} + \beta V^b(\hat{z}) \right\}. \quad (2)$$

If a buyer does not participate in the frictional market then  $\hat{z} = 0$  and

$$W^b(z) = \phi(z + T) + \beta V^b(0). \quad (3)$$

As for sellers, they choose net consumption  $x$  in the centralised market and a nominal price  $p$  for the decentralised market, and have value function

$$W^s(z) = \max_{x, p} \left\{ x + \beta V^s(p) \right\}, \quad \text{subject to} \quad x = \phi z. \quad (4)$$

We now turn to the decentralised market and characterise visit and trading probabilities. For sake of simplicity, we focus on symmetric monetary equilibria in which all sellers charge the same price and all buyers use the same mixed strategy.<sup>5</sup> To facilitate comparison with BSW we use their notation and follow their exposition.

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and Wright's (2001) model, which assumed commitment to a single posted price, but subsequent work (Coles and Eeckhout, 2003; Virag, 2010) has loosened this restriction via a separate multi-buyer posted price or an auction. Anbarci and Feltovich (2013) observed that giving sellers the flexibility to choose a separate multi-buyer price did not lead to different outcomes at the macro level. See Cason and Nossair (2007) and Anbarci and Feltovich (2015) for other tests of posted-price directed-search models.

<sup>5</sup>Due to the finite number of players, there could also be asymmetric equilibria, as well as equilibria in which money is not essential (Aliprantis et al., 2007; Araujo et al., 2012). We focus on symmetric equilibria here because (a) symmetric equilibria have many desirable theoretical properties, such as placing low demands on ability to coordinate and robustness to trembles (Burdett, Shi and Wright, 2001); (b) the relevant theoretical literature typically focuses on symmetric equilibria (Burdett, Shi and Wright, 2001; Coles and Eeckhout, 2003; Lester, 2011); and (c) previous experimental work has found support for homogeneity in behaviour (Cason and Nossair, 2007). There also exist collusive equilibria, though our experimental procedures will rule these out.

Let  $\Phi$  be the probability that at least one buyer visits a particular seller when all buyers visit him with the same probability  $\theta$ . Since  $(1 - \theta)^n$  is the probability that all  $n$  buyers go elsewhere,  $\Phi = 1 - (1 - \theta)^n$ . Next, let  $\Omega$  be the probability that a given buyer gets served when he visits this seller. Since the probability of getting served conditional on visiting this seller times the probability that this buyer visits him equals the probability that this seller serves the particular buyer, we have  $\Omega\theta = \Phi/n$ . Hence

$$\Omega = \frac{1 - (1 - \theta)^n}{n\theta} \quad (5)$$

The Bellman equation for a buyer in the decentralised market is then

$$V^b(z) = \Omega \left\{ Q + W_{+1}^b(z - p) \right\} + (1 - \Omega)W_{+1}^b(z), \quad (6)$$

This equation says that with probability  $\Omega$  a buyer gets served, in which case he purchases and consumes one unit of the search good, paying price  $p$  and receiving instantaneous utility  $Q$ . He then enters the next period's centralised market with  $z - p$  units of money. With probability  $1 - \Omega$  the buyer was not able to trade and proceeds to the centralised market with an unchanged amount of money. The corresponding equation for a seller is

$$V^s(p) = \Phi W_{+1}^s(p) + (1 - \Phi)W_{+1}^s(0), \quad (7)$$

since he trades at price  $p$  (and thus enters the centralised market with  $z = p$  units of money) with probability  $\Phi$ , and otherwise does not trade (and thus has  $z = 0$  units of money).

Now suppose that every seller is posting  $p$ , and one contemplates deviating to  $p^d$ . Let the probability that any given buyer visits the deviant be  $\theta^d$ . By (5), a buyer who visits the deviant gets served with probability

$$\Omega^d = \frac{1 - (1 - \theta^d)^n}{n\theta^d}. \quad (8)$$

Since the probability that he visits each of the non-deviants is  $(1 - \theta^d)/(m - 1)$ , a buyer who visits a non-deviant gets served with probability

$$\Omega = \frac{1 - \left(1 - \frac{1 - \theta^d}{m - 1}\right)^n}{n \left(\frac{1 - \theta^d}{m - 1}\right)}. \quad (9)$$

The corresponding value function for a buyer visiting a deviant seller in the frictional market is given by

$$V^{bd}(z^d) = \Omega \left\{ Q + W_{+1}^b(z^d - p^d) \right\} + (1 - \Omega)W_{+1}^b(z^d). \quad (10)$$

In a symmetric equilibrium of the second-stage game, buyers are indifferent between visiting the deviant seller holding  $p^d$  in cash and any other seller holding  $p$  in cash. Algebraically this means

$$-\phi p + \beta V^b(p) = -\phi p^d + \beta V^{bd}(p^d), \quad (11)$$

where  $\phi p$  and  $\phi p^d$  are the real prices of the search good, expressed in units of the general good. Plugging (6) and (10) into (11), using  $\phi_{+1}(1 + \tau) = \phi$  and  $z = p$ , dividing by  $\beta$  and recalling that  $i = \frac{1 - \beta + \tau}{\beta}$ , Equation (11) simplifies to

$$-ip + \Omega \left( \frac{Q}{\phi_{+1}} - p \right) = -ip^d + \Omega^d \left( \frac{Q}{\phi_{+1}} - p^d \right). \quad (12)$$

Given our assumption of an approximately zero real interest rate, so that  $i \approx \tau$ , we have (approximately)

$$-\tau p + \Omega \left( \frac{Q}{\phi_{+1}} - p \right) = -\tau p^d + \Omega^d \left( \frac{Q}{\phi_{+1}} - p^d \right). \quad (13)$$

As can be seen from Equation (13), inflation acts like a tax by reducing the buyer's surplus by an amount equal to the inflation rate times the amount of money carried,  $\tau p$  (or  $\tau p^d$  if he buys from the deviant).

### 3.3 Symmetric equilibrium

Turning to sellers, expected profit for a deviant seller is identical to that in BSW and given by

$$\pi(p^d, p) = p^d [1 - (1 - \theta^d)^n]. \quad (14)$$

The first-order condition is given by

$$\frac{\partial \pi}{\partial p^d} = 1 - (1 - \theta^d)^n + p^d n (1 - \theta^d)^{n-1} \frac{\partial \theta^d}{\partial p^d} = 0. \quad (15)$$

Assuming  $\theta^d \in (0, 1)$ , we differentiate (13). Inserting equilibrium conditions  $p^d = p$  and  $\theta^d = \frac{1}{m}$ , we extract  $\frac{\partial \theta^d}{\partial p^d}$  which, once inserted into (15), allows us to obtain the equilibrium value of  $p$  as defined in Proposition 1 below.

**Proposition 1** *In the unique symmetric equilibrium, every buyer visits each seller in the frictional market with probability  $\theta^* = 1/m$ , and all sellers set a real price  $\hat{p}^*$  given by*

$$\hat{p}^*(m, n, \tau) = \phi_{+1} \cdot p^* = \frac{[m - 1 - (m + n - 1)(1 - \frac{1}{m})^n] [1 - (1 - \frac{1}{m})^n] m \cdot Q}{[(m - 1)m - ((m - 1)m + n)(1 - \frac{1}{m})^n] [1 - (1 - \frac{1}{m})^n] + \tau n^2 (1 - \frac{1}{m})^{n+1}} \quad (16)$$

Note that the nominal price  $p^*$  is equal to the real price  $\hat{p}^*$  divided by  $\phi_{+1}$ . In other words, real prices, as with all real quantities in the model, are measured in terms of the centralised market's general good.

An immediate corollary of Proposition 1 is that each buyer will choose to hold  $\hat{p}^*$  in real balances. Also, the expected real value of search-good production per market (i.e., the component of real GDP comprised by the decentralised market) is  $\hat{p}^*$  multiplied by the expected number of trades in the market.<sup>6</sup> Since this latter expectation is

$$M(m, n) = m \left[ 1 - \left( 1 - \frac{1}{m} \right)^n \right] \quad (17)$$

(Burdett, Shi and Wright, 2001), the expected real value of search-good production is given by

$$\hat{Y}^*(m, n, \tau) = m \left[ 1 - \left( 1 - \frac{1}{m} \right)^n \right] \hat{p}^*. \quad (18)$$

The associated comparative statics with respect to  $\tau$  are simple. Equations (16) and (18) have right-hand sides with the form  $A/(B\tau + C)$  with  $A, B, C > 0$  and  $\tau \geq 0$ . Therefore both  $\hat{p}^*$  and  $\hat{Y}^*$  are decreasing and convex in  $\tau$ . Of course, since  $\phi_{+1}$  falls as more money is injected (see the constraint in Equation 1), nominal quantities (real quantities divided by  $\phi_{+1}$ ) will increase as inflation rises. Here we are only interested in the real effects of inflation and unless specified all future references to prices or production will mean real prices and real production.

Finally, for completeness we derive the equilibrium value functions. For sellers,

$$\begin{aligned} W^s(z) &= \phi z + \beta V^s(p^*) \\ &= \phi z + \beta \Phi^* W_{+1}^s(p^*) + \beta(1 - \Phi^*) W_{+1}^s(0) \\ &= \phi z + \beta \Phi^* [\phi_{+1} p^* + \beta^2 V_{+1}^s(p^*)] + \beta(1 - \Phi^*) V_{+1}^s(p^*) \\ &= \phi z + \beta \Phi^* \phi_{+1} p^* + \beta^2 V_{+1}^s(p^*) \\ &= \phi z + \beta \Phi^* \phi_{+1} p^* - \beta \phi_{+1} z + \beta W_{+1}^s(z), \end{aligned}$$

<sup>6</sup>We will concern ourselves with production per market rather than the total level, for the sake of comparability across experimental sessions with different numbers of markets. For readability, we will sometimes leave out "per market", though this is always implied.



where  $p^*$  is given by (16) and  $\Phi^* = 1 - \left(\frac{m-1}{m}\right)^n$  is the equilibrium probability of a given seller being visited. Thus,

$$W^{s*}(z) = \frac{1}{1-\beta} [(\phi - \beta\phi_{+1})z + \beta\Phi\phi_{+1}p^*] = \frac{\beta\phi_{+1}(i \cdot z + \Phi p^*)}{1-\beta}. \quad (19)$$

For buyers,

$$\begin{aligned} W^b(z) &= \phi(z + T - p^*) + \beta V^b(p^*) \\ &= \phi(z + T - p^*) + \beta\Omega^*[Q + W_{+1}^b(0)] + \beta(1 - \Omega^*)W_{+1}^b(p^*) \\ &= \phi(z + T - p^*) + \beta\Omega^*[Q + \phi_{+1}(T - p^*) + \beta V_{+1}^b(p^*)] + \beta(1 - \Omega)[\phi_{+1}T + \beta V_{+1}^b(p^*)] \\ &= \phi(z + T - p^*) + \beta\Omega^*(Q - \phi_{+1}p^*) + \beta\phi_{+1}T + \beta^2 V_{+1}^b(p^*) \\ &= (\phi - \beta\phi_{+1})(z - p^*) + \phi T + \beta\Omega^*(Q - \phi_{+1}p^*) + \beta W_{+1}^b(z), \end{aligned}$$

where  $\Omega^* = \frac{m}{n} \left[1 - \left(\frac{m-1}{m}\right)^n\right]$  is the equilibrium probability of a given buyer being able to buy. Thus,

$$W^{b*}(z) = \frac{1}{1-\beta} [\phi T + \beta i \phi_{+1}(z - p^*) + \beta\Omega^*(Q - \phi_{+1}p^*)]. \quad (20)$$

The corresponding expressions for  $V^{b*}(z)$  and  $V^{s*}(p^*)$  can be found by substituting (19) into (6) and (20) into (7), respectively.

## 4 The experiment

Our experiment implemented this model in a way that preserves the incentives facing buyers and sellers while simplifying parts that are less relevant to our research questions. We present an overview of the experimental design and procedures in this section, with additional methodological details in Appendix A for the interested reader.

### 4.1 Experimental design and procedures

In the experiment, there were two types of market (2[seller]x2[buyer] or 3x2) and three inflation rates (0%, 5% or 30%). We manipulated the number of sellers in the experiment in order to determine the robustness of the effect of the inflation rate to different markets.<sup>7</sup> Inflation rates of 0% and 5% were chosen because they roughly bracket the actual rates seen in many developed countries now and in the recent past. Our other inflation rate of 30% is high by today's standards, at least in developed countries, but is comparable to the highest levels seen in those countries outside of hyperinflations. (E.g., inflation in the UK in 1974 was estimated at over 24%.) We set  $Q$  equal to 20 units of the general good, as per the model where real values are measured in units of the general good.<sup>8</sup> The choice of 20 itself is without loss of generality because a different value of  $Q$  would leave relative variables (e.g., per-cent changes, elasticities) unaffected, and imply only a re-scaling of absolute variables (e.g., prices). For simplicity we set one unit of the general good equal to one Australian dollar (AUD).<sup>9</sup> So, even though prices and profits were

<sup>7</sup>That is, our concern is not with the effect of market structure per se. We therefore do not state hypotheses concerning the number of sellers. Of course, the model clearly implies that increasing the number of sellers results in lower prices (Figure 2 and Table 1), and although we do not emphasise the corresponding results in the following sections, the interested reader can verify that the predicted effects are observed in the data.

<sup>8</sup>Because instantaneous utility functions are linear in net consumption of the general good (see Section 3.2), buyer valuations and seller costs for the search good can also be denominated in units of the general good.

<sup>9</sup>At the time of the experiment, the Australian and US dollars were roughly at parity, while the *Economist's* Big Mac index estimated their purchasing powers at approximately 1.08 AUD = 1 USD on 30 January 2013 (Economist, 2013).

stated – and payments to the subjects were made – in AUD, the one-to-one exchange rate meant that subjects were effectively thinking in real terms, i.e., in units of the general good.

Subjects in the experiment played 54 replications (“rounds”) of a one-shot stage game that corresponds to the infinite-horizon game analysed in Section 3. Specifically, a round of the experiment began in the first sub-period of the initial period (i.e., the centralised market), with all subjects having zero cash holdings. Subjects played that entire period – both centralised and decentralised markets – and then participated in the beginning of the second period’s centralised market, but only in order to re-balance their cash holdings to zero. At this point, the round and hence the infinite-horizon game ended for the subjects.<sup>10</sup> After receiving some feedback regarding the results of that round, a new round began, again at the first sub-period of the first period, and again with zero cash holdings. A seller’s profit in a round was her posted price if she was able to sell her unit of the search good (i.e., she produces at zero cost and sells at the posted price), and zero otherwise. A buyer’s profit was his valuation of 20 minus the price paid if he was able to buy a unit of the search good (corresponding to the consumer surplus realised by consuming the good), or zero if not, minus the inflation tax in either case. In Appendix B, we demonstrate that this simplified one-shot setting preserves the incentives of the infinite-horizon setting analysed in Section 3, in the sense that for any set of choices that is possible in an experimental round, the resulting profit is an affine function of the lifetime utility yielded by the same set of choices in the corresponding portion of the infinite-horizon setting, combined with optimal behaviour in the continuation.<sup>11</sup>

Each subject faced all three inflation rates (within-subject variation), within one of the two markets (between-subject variation). The 54 rounds were split into three blocks of 18 rounds, each with a different inflation rate, and with the ordering of the inflation rates varied to control for order effects. Subjects kept the same role (buyer or seller) in all rounds, but were randomly assigned to markets in each round, so as to preserve the one-shot nature of the stage game by having subjects interact with different people from round to round. Some large sessions were partitioned into two “matching groups” that were closed with respect to interaction (i.e., subjects in different matching groups were never assigned to the same market), allowing two independent observations from the same session.

The experiment was computerised, and programmed using the *z-Tree* experiment software package (Fischbacher, 2007). Subjects were primarily Monash University undergraduates. All interaction took place anonymously via the computer program; subjects were visually isolated and received no identifying information about other subjects (not even persistent ID numbers). Instructions were given in writing and orally, the latter in an attempt to make the rules common knowledge.<sup>12</sup> For the same reason, the inflation rate was announced publicly whenever it changed (before rounds 1, 19 and 37).

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<sup>10</sup>The re-balancing done immediately before this truncation is equivalent to our imposing the credibility of fiat money. Subjects with positive cash balances at the end of the first period (e.g., sellers who sold) are assumed to be able to find a counter-party willing to accept their cash in return for the general good. Subjects with negative cash balances at this point are constrained by the experimental program to sell the general good to get their cash balance up to zero.

<sup>11</sup>The specific affine transformation we used involved subtracting the continuation value – given a zero cash holding at the time the experimental round ended – from lifetime utility. This made it possible to provide the experimental subjects with a much-simplified description of the decision-making environment, since it was not necessary to explain the concept of continuation value to them, while still preserving the incentives of the infinite-horizon problem. We note here that assuming optimal continuation behaviour is itself a suspect assumption, since almost all studies of behaviour in the lab and field find at least a background level of decision errors. Nonetheless, we impose this assumption because (a) no clear alternative assumption regarding continuation behaviour exists, and (b) having subjects play (e.g., under indefinite repetition of the stage game) and observing their continuation behaviour would come at the cost of having fewer rounds and hence lower power to detect the treatment effects we are interested in.

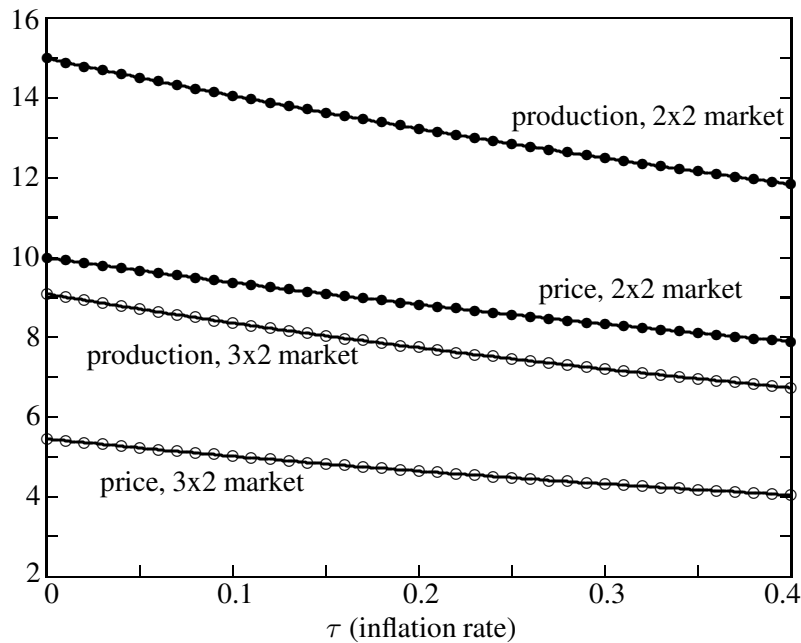
<sup>12</sup>See Appendix C for the instructions and Appendix D for sample screen-shots. Other experimental materials and the raw data are available from the corresponding author upon request.

At the end of the last round, subjects were paid, privately and individually, the sum of their profits from six randomly chosen rounds out of the 54, in Australian dollars. Total earnings averaged just under \$50 and ranged from \$10 to \$102.10, for a session that typically lasted about 90 minutes.

## 4.2 Hypotheses

Our hypotheses are based on the implications of Proposition 1. The predicted effects of the inflation rate  $\tau$  on price (which henceforth will mean the real period-1 price of the search good) and per-market value of production of the search good, based on  $m = 2$  or 3 sellers,  $n = 2$  buyers and a buyer valuation of  $Q = 20$ , are shown in Figure 2, and for the specific inflation rates used in the experiment ( $\tau = 0, 0.05, 0.30$ ), in Table 1. (Recall that price and production of the search good are measured equivalently in units of the general good or in AUD.) The table also shows the

Figure 2: Predicted real prices (= per-buyer cash holdings) and real per-market production of the search good



corresponding semi-elasticities with respect to the inflation rate; these are calculated as  $\frac{\partial \ln(p^*)}{\partial \tau}$  and  $\frac{\partial \ln(Y^*)}{\partial \tau}$ , and can be interpreted as the proportion change in price or production associated with a 1-percentage-point change in the inflation rate. (From (18),  $Y^*$  is a constant multiplied by  $p^*$ , so both variables have the same semi-elasticity.)

As shown in the figure and the table, raising the inflation rate (*ceteris paribus*) leads to lower real prices and lower real production of the search good, though the size of this predicted effect decreases as inflation increases, as shown by the lower magnitudes of semi-elasticities at higher inflation rates. We therefore have:

**Hypothesis 1** *Holding the market constant, real prices and real production will decrease as the inflation rate increases.*

**Hypothesis 2** *Holding the market constant, the magnitude of the effect of inflation on real prices and real production will decrease as the inflation rate increases.*

Table 1: Theoretical predictions for the treatments used in the experiment

Market	Inflation rate	Real price	Real production/market	Semi-elasticity
2x2	0%	10.00	15.00	-3.00
	5%	9.68	14.52	-2.90
	30%	8.33	12.50	-2.50
3x2	0%	5.45	9.09	-5.58
	5%	5.23	8.71	-5.35
	30%	4.32	7.20	-4.42

*Note: semi-elasticity is proportion change in price or production of the search good associated with a 1-percentage-point change in the inflation rate.*

## 5 Experimental results

We conducted fourteen experimental sessions (not including four earlier pilot sessions, with some differences in model parameters and manipulated variables, and which we do not discuss further in this paper), with a total of 193 subjects.

### 5.1 Observed market aggregates

Table 2 reports aggregate experimental data for our main variables of interest. Two measures of price are shown: the average real posted price (i.e., the actual choices of sellers) and the average real transaction price (those posted prices at which a unit was traded). Also shown is real production per market of the search good (the total value of units traded). These averages are shown for each combination of market (2[seller]x2[buyer] or 3x2) and inflation rate ( $\tau = 0\%$ , 5% or 30%).

Table 2: Aggregate observed market data

Inflation rate (%):	2x2 market			3x2 market		
	0	5	30	0	5	30
Posted price (real)	11.64	10.32	9.13	7.93	6.86	5.26
Transaction price (real)	11.48	10.04	8.90	7.24	6.32	4.87
Production (real)	16.97	14.73	13.33	12.22	10.29	7.83

Consistent with Hypothesis 1, the table shows a negative association between the inflation rate  $\tau$  and real posted prices, transaction prices and production. Non-parametric statistical tests on the matching-group-level data verify this effect.<sup>13</sup> Page tests reject the null hypothesis of no difference across the three inflation rates in favour of

<sup>13</sup>See Siegel and Castellan (1988) for descriptions of the non-parametric tests used in this paper, and Feltovich (2006) for critical values for the robust rank-order tests used later in this section. As noted in Section 4.1, the matching group is the smallest independent unit of aggregation, making it the appropriate unit for non-parametric tests. We note here that although there is non-negligible dispersion in posted prices – ranging from 1.97 in the 3x2 market with 30% inflation to 2.64 in the 2x2 market with 0% inflation – there are no significant differences in price dispersion across inflation rates within either market (Friedman two-way analysis of variance,  $F = 2.89$  and  $F = 4.22$

an ordered alternative hypothesis – decreasing price and production as  $\tau$  increases – at the 0.1% level for both markets and for all three variables, except for production in the 2x2 market, where significance is at the 1% level. Additionally, pairwise Wilcoxon signed-ranks tests (for matched samples) reject the null hypothesis of no difference in outcome variable between  $\tau = 0$  and  $\tau = 0.05$ , and between  $\tau = 0.05$  and  $\tau = 0.30$ , at the 1% level for both markets and all three variables, with only two exceptions ( $p \approx 0.02$  for the difference in transaction prices between  $\tau = 0$  and  $\tau = 0.05$  in the 3x2 market, and  $p \approx 0.04$  for the difference in production between  $\tau = 0.05$  and  $\tau = 0.30$  in the 2x2 market).

Table 2 also provides suggestive evidence in favour of Hypothesis 2, as the impact of the rise in inflation from 0% to 5% on prices and production is relatively larger than that of the rise from 5% to 30% (i.e., accounting for the fact that the latter is five times as large an increase in the inflation rate). In Table 3, we look more closely at inflation’s effects at different inflation levels, by calculating semi-elasticities based on the aggregate data found in Table 2. For

Table 3: Semi-elasticities based on aggregate observed market data (percent change in market variable associated with a one-percentage-point rise in the inflation rate)

Inflation rate interval (%):	2x2 market			3x2 market		
	0–5	5–30	<i>p</i> -value, signif. of differences	0–5	5–30	<i>p</i> -value, signif. of differences
Posted price (real)	-2.38	-0.49	$p \approx 0.01$	-2.86	-1.06	$p \approx 0.06$
Transaction price (real)	-2.64	-0.48	$p \approx 0.01$	-2.68	-1.03	$p \approx 0.10$
Production (real)	-2.79	-0.40	$p \approx 0.04$	-3.38	-1.09	$p \approx 0.05$

each variable (posted prices, transaction prices and production) and market (2x2 and 3x2), we compute the percent change in the variable associated with a one-percentage-point rise in the inflation rate, over the interval from 0% to 5% and over the interval from 5% to 30%.<sup>14</sup> Table 3 also reports the results of Wilcoxon signed-ranks tests of differences between semi-elasticities from 0% to 5% inflation and corresponding ones from 5% to 30% inflation (again using matching-group-level data). In all six cases, inflation’s impact is higher over the low interval than over the high interval, and in five of the six, the difference is significant at the 10% level or better (for transaction prices in the 3x2 market, the *p*-value is 0.102, just missing significance at the 10% level).

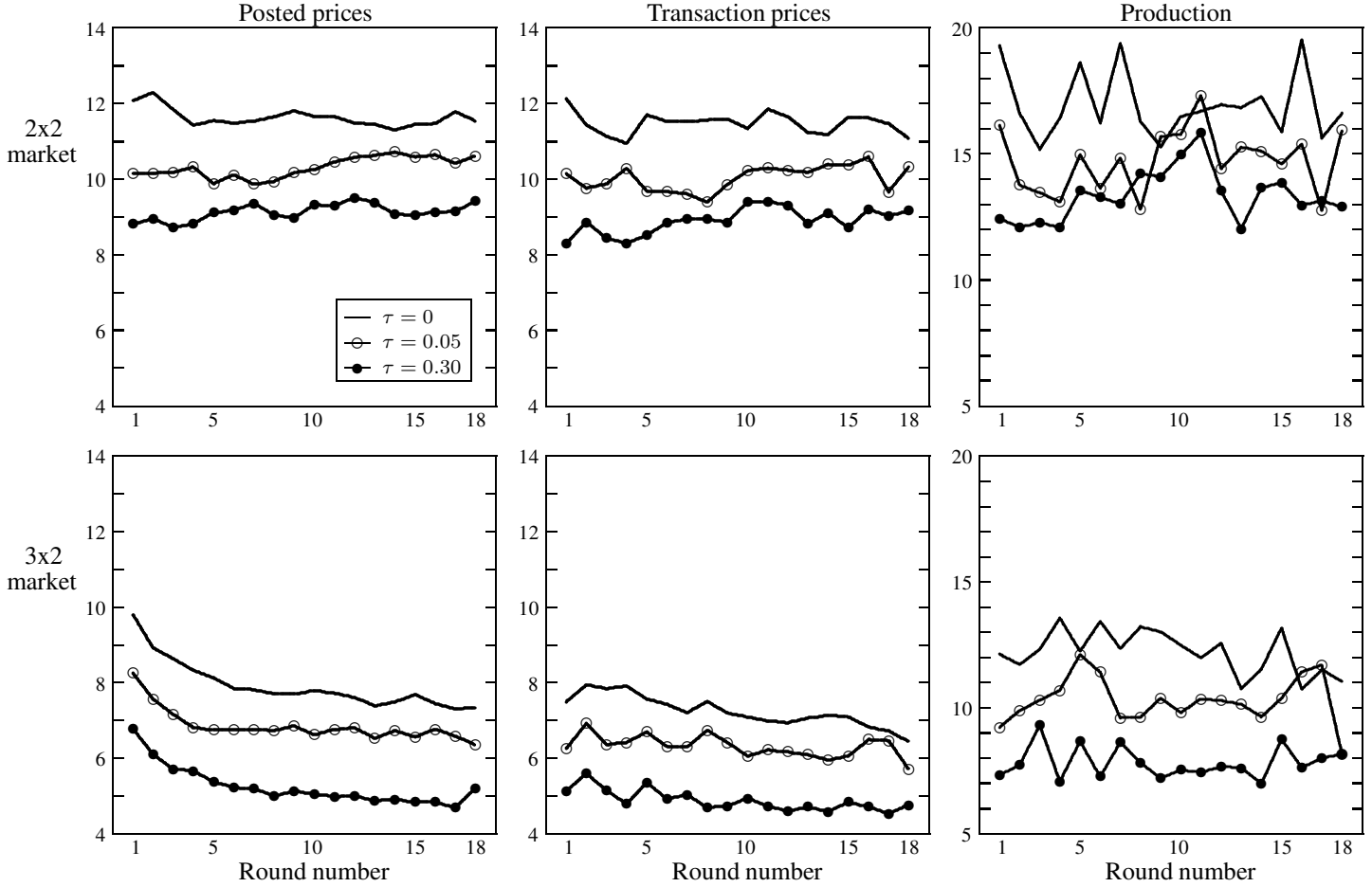
Figure 3 shows the time series of posted and transaction prices and production for each market and inflation rate. Differences in prices across inflation rates are fairly stable over time, as are the prices themselves with one exception: posted prices in the 3x2 market, where there is a steady downward trend over the first several rounds.<sup>15</sup> Differences in production across inflation rates are somewhat noisier, but the noise doesn’t obscure the treatment effect, and we observe no systematic time trend in these either.

for 2x2 and 3x2 markets respectively,  $p > 0.10$  in both cases).

<sup>14</sup>We compute the semi-elasticity as the value  $\epsilon$  that solves  $x_{\tau_2} = x_{\tau_1}(1 - \epsilon)^{\tau_2 - \tau_1}$ , multiplied by 100 to be expressed as a percent. Note that these are interval semi-elasticities, as opposed to point semi-elasticities such as those displayed in Table 1. We computed point semi-elasticities there because we were working from the theory, and thus knew the exact formula for price as a function of the inflation rate. Here, we have no functional form to work with, so we calculate average semi-elasticities from the data.

<sup>15</sup>This downward trend, combined with the lack of time trend in transaction prices, suggests that many sellers in the 3x2 market initially fail to appreciate the substantial market power buyers have in this market, choose prices that would have been better suited to a market with a more equitable distribution of market power, fail to sell at these prices, and learn to choose lower prices in subsequent rounds. Other explanations are possible.

Figure 3: Time series of real posted prices, real transaction prices and real production by inflation rate



## 5.2 Parametric analysis of prices and production

We move to regressions with real posted price, real transaction price and real production as the dependent variables. Our primary explanatory variables are indicators for inflation rates of 0.05 and 0.30 (with 0 as the baseline) and an indicator for the 3x2 market. To allow for time-varying effects, we include the round number (running from 1 to 18, and re-starting at 1 when the inflation rate changes) and its square on the right-hand side, as well as all of the two- and three-way interactions between the inflation-rate, 3x2-market, and round-number variables.

We also include a number of “nuisance” variables. To control for the possibility of order effects due to our within-subject variation of the inflation rate, we include indicator variables for the 0.05–0.30–0.00 and 0.30–0.00–0.05 inflation-rate orderings, and to control for learning, we include indicators for the second and third inflation rates in a session (equivalent to the second and third block of 18 rounds). Finally, to control for the possibility that sellers attempt to tacitly collude (due to our repetition of the stage game), we include the number of sellers in the entire session (which was observable to subjects) and the number of sellers in the matching group (not observable, but included in case subjects somehow managed to infer this). Descriptive statistics for these variables are shown in Table 4. We use Stata (version 12) to estimate panel Tobit models with endpoints 0 and 20, and with individual-seller random effects.

Table 5 reports the estimation results: marginal effects (taken at variables’ means) and standard errors. These

Table 4: Descriptive statistics for variables used in regressions

Variable	Mean	Std. Dev.	Min.	Max.
Posted price	8.20	3.14	0.00	20.00
Transaction price	8.09	3.12	0.00	19.00
Production (per market)	12.62	6.27	0.00	36.65
$\tau = 0.05$ dummy	0.333	0.471	0	1
$\tau = 0.30$ dummy	0.333	0.471	0	1
3x2-market dummy	0.589	0.492	0	1
Round number	9.50	5.189	1	18
Second-inflation-rate dummy	0.333	0.471	0	1
Third-inflation-rate dummy	0.333	0.471	0	1
0.05-0.30-0.00 ordering	0.326	0.469	0	1
0.30-0.00-0.05 ordering	0.326	0.469	0	1
Number of sellers (session)	8.03	1.84	6	12
Number of sellers (group)	6.46	1.81	4	9

results reinforce the non-parametric test results presented earlier. Consistent with Hypothesis 1, both inflation-rate dummies have the predicted negative effect on both measures of price and on production, and all six of these effects are significant ( $p < 0.001$ ). Examination of the other variables indicates that prices and production are lower in the 3x2 market than in the 2x2 market, and there is some evidence of learning across as well as within blocks (with lower prices for the second and third blocks, and over rounds within a block), while there are few significant order effects amongst the inflation rates, and the number of sellers in either the session or the matching group has no significant effect.

While Table 5 shows that the inflation tax has an effect on prices and production, it sheds little light on curvature: does the effect change more or less quickly at high inflation rates than low ones? A straight comparison of the  $\tau = 0.05$  and  $\tau = 0.30$  dummies finds that the latter has a significantly larger effect ( $p < 0.002$  in all three regressions), but this comparison doesn't tell the whole story, since the  $\tau = 0.30$  dummy represents a change in inflation six times the size of that of the  $\tau = 0.05$  dummy. In Table 6, we make a like-for-like comparison by estimating the ratio of the respective semi-elasticities: that is, the ratio between the effects of a one-percentage-point change in the inflation rate between 0% and 5% inflation (i.e., the marginal effect of the  $\tau = 0.05$  dummy, divided by five) and the same change between 5% and 30% inflation (i.e., the difference in marginal effects between the  $\tau = 0.30$  and  $\tau = 0.05$  dummies, divided by 25). The table reports the point estimate of this ratio of semi-elasticities for posted price, transaction price, and production, separately for the 2x2 and 3x2 markets, and for the two markets pooled together. Also shown in the table are the corresponding 95% confidence intervals.

The results in this table are fairly striking, and consistent with those seen in Table 3 (thus supporting Hypothesis 2). The nine point estimates vary between about 3 and 11, well above the value of unity that would imply a linear effect of the inflation rate. In the case of production, the confidence intervals for the two individual markets are wide enough to include 1, so that we can't reject the null hypothesis of a linear effect except for the two markets pooled together; however, for both price variables, 1 is well outside any of the confidence intervals, confirming that changes in the inflation rate have larger effects under low inflation than under high inflation.

Table 5: Tobit results – estimated marginal effects on real posted price, real transaction price and real production (at variable means) and standard errors

Dependent variable:	Posted price	Transaction price	Production
$\tau = 0.05$ dummy	−1.090*** (0.086)	−1.123*** (0.094)	−1.985*** (0.385)
$\tau = 0.30$ dummy	−2.513*** (0.086)	−2.427*** (0.094)	−3.756*** (0.382)
<i>Significance of difference:</i>	$p < 0.001$	$p < 0.001$	$p < 0.001$
3x2–market dummy	−3.850*** (0.356)	−3.855*** (0.359)	−4.289*** (0.806)
Round number	−0.042*** (0.005)	−0.015*** (0.005)	−0.001 (0.020)
Second–inflation–rate dummy	−0.298*** (0.057)	−0.132** (0.063)	−0.482* (0.257)
Third–inflation–rate dummy	−0.219** (0.057)	−0.063 (0.063)	−0.194 (0.257)
0.05–0.30–0.00 ordering	−0.371 (0.350)	−0.340 (0.353)	−0.739 (0.777)
0.30–0.00–0.05 ordering	−0.494 (0.384)	−0.569 (0.387)	−1.517* (0.816)
Number of sellers (session)	0.032 (0.093)	−0.023 (0.094)	0.038 (0.210)
Number of sellers (matching group)	−0.041 (0.096)	−0.066 (0.097)	−0.290 (0.211)
Constant term?	Yes	Yes	Yes
Interaction effects?	Yes	Yes	Yes
$N$	5778	3620	2322
$ \ln(L) $	11717.97	6875.85	7129.02

\* (\*\*,\*\*\*): Coefficient significantly different from zero at the 10% (5%, 1%) level.

Table 6: Estimated ratio of marginal effects of one–percentage–point rise in inflation based on Table 5 models

Market	Posted price		Transaction price		Production	
	Point estimate	95% C.I.	Point estimate	95% C.I.	Point estimate	95% C.I.
2x2	5.954	(3.565, 8.343)	6.152	(3.770, 8.534)	11.043	(−6.667, 28.752)
3x2	2.922	(2.012, 3.831)	3.094	(1.890, 4.299)	3.885	(0.810, 6.959)
Signif. of difference:	$p \approx 0.020$		$p \approx 0.025$		$p > 0.20$	
Pooled 2x2 and 3x2	3.831	(2.921, 4.741)	4.307	(3.162, 5.451)	5.607	(1.687, 9.528)

Notes: Ratio defined as  $(5 \cdot \beta_{\tau=0.05}) / (\beta_{\tau=0.30} - \beta_{\tau=0.05})$ , where  $\beta_{\tau=x}$  is the marginal effect of the “ $\tau = x$ ” dummy. A value of 1 indicates a linear effect of  $\tau$ ; larger values indicate a diminishing marginal effect.

### 5.3 Buyer behaviour

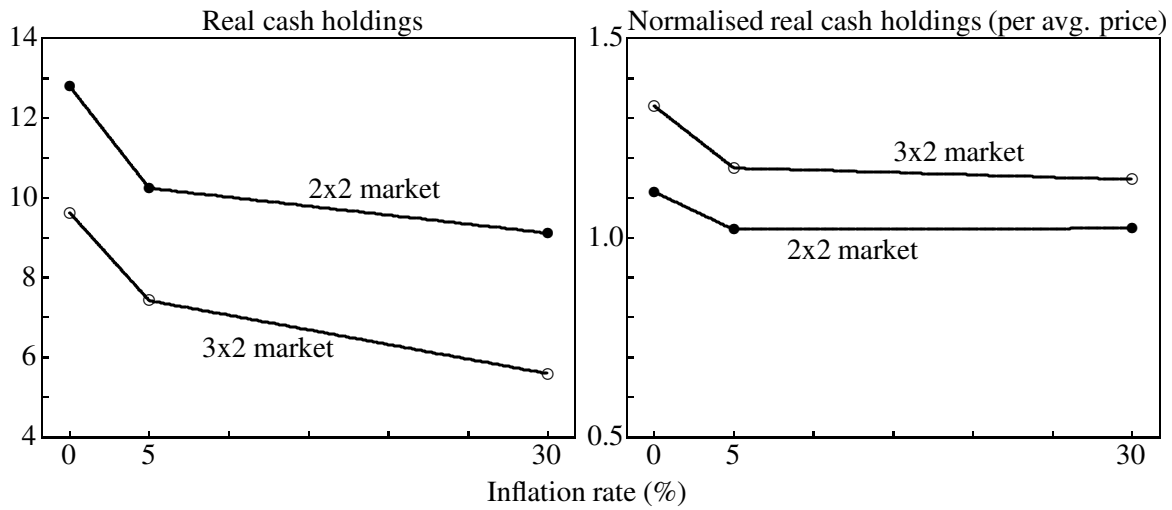
We move to an examination of buyers’ behaviour. Buyers make two inter–connected decisions: how much cash to hold, and which seller to visit. Both of these decisions are worthy of study not only for their own sake, but because of their role in determining transaction prices and thus the value of production, and indirectly in shaping the incentives sellers face when choosing their posted prices. We look at cash holdings here, and at visit decisions in Section 5.5.

Figure 4 shows, for both markets, how average cash holdings change with the inflation rate. The left panel



shows a money demand curve for each market (at each inflation rate, the average amount of cash held by all buyers). These curves replicate patterns found in real data (see, e.g., Lucas, 2000, Figures 2 and 3, or Lagos and Wright,

Figure 4: Buyer behaviour – demand for money



2005, Figure 2), with cash holdings declining as the inflation rate increases. The right panel shows those same average cash holdings, normalised for each combination of market and inflation rate by dividing by the associated mean transaction price. Even normalised (in terms of average prices), money demand tends to decrease as inflation increases (though the difference from 5% to 30% inflation is close to zero in both markets).<sup>16</sup>

## 5.4 Welfare cost of inflation

We have already documented that a rise in inflation hurts the aggregate economy via falling production (see Table 2). In this section we take advantage of the framework we have built and the data we collected in the experiment to compute an estimate of the welfare costs of inflation in our economy.

In our experiment, whenever a transaction occurs, the buyer receives a consumer surplus equal to the difference between his valuation for the good and the seller's posted price, less the amount of the inflation tax incurred in order to participate in the market. The seller receives a producer surplus equal to her posted price (since the cost of production is zero). The natural measure of absolute welfare is then the sum of consumer and producer surplus per market, and consequently welfare loss is the difference in total surplus between zero inflation and a given positive inflation rate.<sup>17</sup> Table 7 summarises the findings.

On average, raising inflation from 0% to 5% is associated with a 5 percent decrease in total surplus, with the loss somewhat higher in the 3x2 market than in the 2x2 market, although the difference is not significant (robust rank-order test,  $p > 0.20$ ). Further increases in inflation lead to additional welfare losses, though the rate of increase slows as inflation rises; the total decrease in surplus as inflation rises from 0% to 30% averages roughly 15 percent,

<sup>16</sup>The negative overall relationship between inflation and money demand continues to hold if we instead put nominal or real cash holdings *net of the price paid* on the vertical axis. Thus, *excess cash holdings* – beyond what buyers actually need to hold in order to buy – decrease as inflation increases. This effect is seen in both the extensive and intensive margins (as inflation rises, excess cash is held less often, and the amount held conditional on being positive is smaller).

<sup>17</sup>Note that welfare is measured in units of the general good, and also that within each round of the experiment, welfare equals total subject profit, which is the standard measure of well-being used in analysis of economics experiments.

Table 7: Total surplus (consumer + producer) per market, and welfare loss from inflation

	2x2 market	3x2 market
Total surplus, 0% inflation	29.55	33.76
Total surplus, 5% inflation	28.32	31.85
Total surplus, 30% inflation	24.48	28.76
Welfare loss, 0%-5%	4.2%	5.7%
Welfare loss, 0%-30%	17.2%	14.8%

and is significantly larger in the 2x2 market than in the 3x2 market (robust rank–order test,  $p \approx 0.05$ ).

For low levels of inflation, we thus find welfare losses to be higher than previous measures using field data have found. (By comparison, the largest effect mentioned in Section 2 is a 7 percent welfare loss from a 10–percentage–point rise in inflation, in one of Burstein and Hellwig’s (2008) cases.) They are not directly comparable, however. A first obvious difference is that our experimental approach gives us access to information such as exact buyer valuations and seller costs, allowing their use in our calculations. Such information would be at best difficult, and at worst impossible, to obtain from field data.<sup>18</sup> Second, our measure deducts the inflation tax in full from total surplus. In a general equilibrium model, however, the inflation tax contributes to the gross income of some lending institutions and therefore cannot be subtracted in full.

## 5.5 Buyer visit choices

In Figure 5, we examine the other component of buyer behaviour – the choice of which seller to visit. We begin by noting that in a given market and round, the profile of seller prices and inflation rate gives rise to a symmetric subgame played between the two buyers. Each buyer has  $m+1$  pure strategies: one for visiting each of the  $m$  sellers, and another strategy we might call “stay home”. (Even though buyers in our experiment are required to visit a seller, they can “stay home” by choosing to hold zero cash.) Staying home yields a certain payoff of zero; visiting a seller yields a expected payoff that depends on that seller’s price and the inflation rate. This game often, but not always, has multiple Nash equilibria; however, it is easy to show that there is always a unique *symmetric* Nash equilibrium. This symmetric equilibrium is the one used in Section 3.3 to find the equilibrium in seller price choices, and is the one selected by Burdett, Shi and Wright (2001) and others; because buyers in the model have no external information on which to coordinate on an asymmetric equilibrium, the symmetric equilibrium is eminently reasonable.

From this symmetric equilibrium, we construct a *reliability diagram*, showing how closely the predicted and actual probabilities of visiting a seller correspond. This is known as the *calibration* (Yates, 1982) of mixed–strategy equilibrium as a predictor of buyer visit choices.<sup>19</sup> The reliability diagram is constructed as follows. First, for each buyer and round, the predicted probability of visiting each seller is computed, and the associated actual visit

<sup>18</sup>Hence, welfare–loss measures using field data tend to be *compensated*; i.e., they don’t measure welfare directly (since they cannot), but instead measure the amount of some other variable, such as income or consumption, that agents would have to gain in order to offset a rise in inflation. Our measure can also be thought of as a compensated measure, since it also represents the change in consumption of the general good that would offset the effect of the inflation tax.

<sup>19</sup>For example, if calibration is high, then in all cases where mixed–strategy equilibrium predicts Seller 1 is visited with probability 0.4, buyers should actually have chosen to visit that seller four–tenths of the time; and when the predicted probability is 0.7, she should have been visited seven–tenths of the time by any given buyer; and so on.

choice is recorded.<sup>20</sup> Second, for a given seller number and for each of thirteen intervals of predicted probability, the average of all the predicted probabilities lying in the interval is calculated, as is the frequency of actual visits to that seller in those occurrences.<sup>21</sup> Then, a circle is plotted at the ordered pair (average predicted probability, actual frequency), with an area proportional to the number of occurrences. As an example, one of the intervals we used was the singleton  $\{0.5\}$ . If there were 100 cases where the predicted probability of visiting Seller 1 was 0.5, and the buyers actually visited Seller 1 in 47 of those cases, a circle would be plotted at  $(0.5, 0.47)$ , with area proportional to 100.

Figure 5: Buyer behaviour – symmetric Nash equilibrium probability of visiting Seller 1 versus actual frequency of visits to Seller 1 (area of a circle is proportional to the number of observations it represents)

Observed frequency of Seller 1 visits

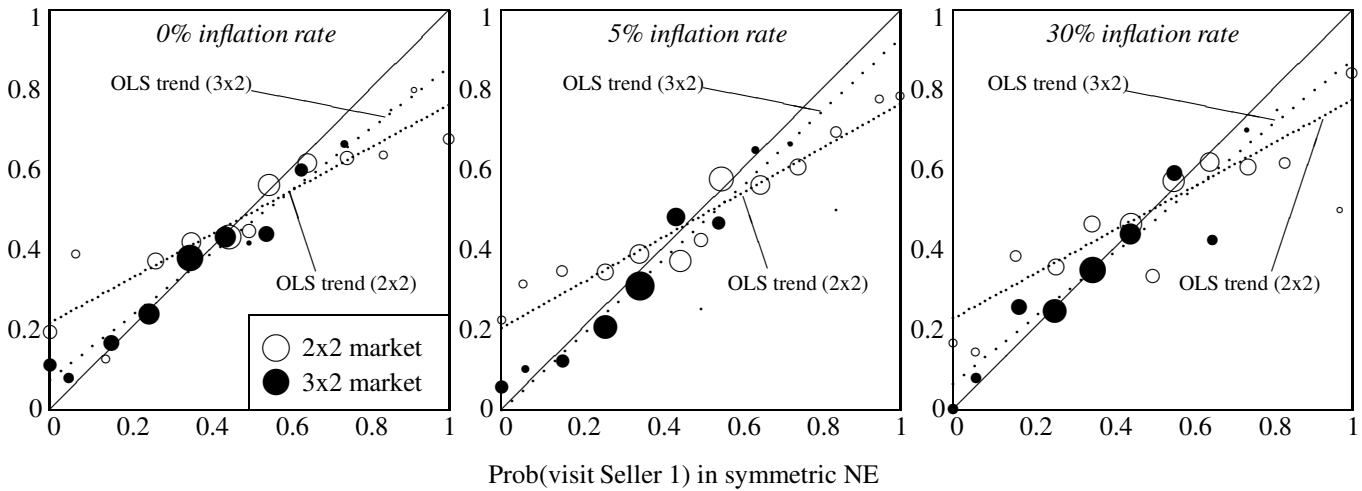


Figure 5 is the result of this process for visits to Seller 1 (using a different seller number has no qualitative impact), with circles plotted separately for 2x2 and 3x2 markets, for each of the three inflation rates, and for each of the thirteen intervals. Also shown are OLS trend lines for each market and inflation rate, along with the 45-degree line (where predicted and observed probability are equal, and hence calibration is perfect).

Two aspects of buyer visit behaviour are apparent. First, calibration varies between the two markets: buyers in the 3x2 market are remarkably well calibrated, with actual visit frequencies very close to the corresponding predicted probabilities in all three panels, while buyers in the 2x2 market tend to visit a seller too often when the predicted probability is low, and too seldom when it is high. Since predicted probability is based primarily on the seller’s price relative to the other seller price(s) – along with the inflation tax – this result means that buyers are insufficiently price-elastic compared to the theory in the 2x2 market, while they have roughly the right level of price sensitivity in the 3x2 market.<sup>22</sup>

<sup>20</sup>As it turns out, in every observation in the experiment, sellers’ prices were such that staying home was always strictly dominated by visiting at least one of the sellers, so the predicted probability of staying home was always zero.

<sup>21</sup>Our intervals are  $\{0\}$ ,  $(0, 0.1]$ ,  $(0.1, 0.2]$ ,  $(0.2, 0.3]$ ,  $(0.3, 0.4]$ ,  $(0.4, 0.5]$ ,  $\{0.5\}$ ,  $(0.5, 0.6]$ ,  $(0.6, 0.7]$ ,  $(0.7, 0.8]$ ,  $(0.8, 0.9]$ ,  $(0.9, 1)$ ,  $\{1\}$ .

<sup>22</sup>Either risk aversion or loss aversion would imply less price elasticity than under expected-payoff maximisation. However, the results in Figure 5 are not solely due to risk aversion, as risk aversion also implies *lower* price elasticity in the 3x2 market than in the 2x2 market, rather than the higher sensitivity that we observe. Loss aversion, on the other hand, does imply higher price elasticity in the 3x2 market than in the 2x2 market, and therefore can explain the *qualitative* relationships we observed. It has less success in characterising behaviour *quantitatively*,

Second, there are no economically relevant differences in calibration across inflation rates within either the 2x2 or 3x2 market. This apparent lack of difference is given further support by a panel probit regression, with Seller 1 visit as the dependent variable (again, using a different seller number doesn't change the conclusions), and with the predicted probability, a dummy for the 3x2 market, and dummies for inflation rates of 5% and 30% on the right-hand side, along with all interactions and a constant term. The results are shown in Table 8.

Table 8: Marginal effects of selected factors on observed frequency of Seller 1 visits (panel probit)

Average marg. effects (std. errors)		Marg. effects of predicted prob. at particular variable values				
Predicted prob.		Inflation rate	2x2 market		3x2 market	
			Point est.	95% CI	Point est.	95% CI
	0.703*** (0.033)					
$\tau = 0.05$	-0.014 (0.017)	0%	0.557	(0.420, 0.694)	0.805	(0.641, 0.969)
$\tau = 0.30$	0.006 (0.017)	5%	0.558	(0.412, 0.704)	0.989	(0.817, 1.160)
3x2 market	-0.043** (0.018)	30%	0.555	(0.412, 0.698)	0.828	(0.655, 1.001)

Notes:  $N = 4644$ ,  $|LL| = 2888.21$ . (\*, \*\*, \*\*\*): Coefficient significantly different from zero at the 10% (5%, 1%) level.

The left column shows that the marginal effect of the predicted probability is positive but significantly less than one ( $p < 0.001$ ), implying that buyers do respond to prices in their visit choices, but they are less price-elastic than they should be, as Figure 5 illustrated. The right side of the table shows marginal effects of the predicted probability for each combination of market and inflation rate: clearly, responsiveness is higher in the 3x2 market than in the 2x2 market, and these differences are significant at each inflation rate ( $p < 0.001$  at 0% inflation,  $p \approx 0.024$  at 5%,  $p \approx 0.019$  at 30%). On the other hand, there is no difference in responsiveness across the three inflation rates within a market ( $p \approx 0.99$  in the 2x2 market,  $p \approx 0.26$  in the 3x2 market).<sup>23</sup> As always, we must be careful in drawing any positive conclusion from a failure to reject null hypotheses, but based on these high  $p$ -values, we are fairly confident that there actually is no difference in buyer' price elasticity across inflation rates.

It is worth commenting on this lack of difference across inflation rates. As mentioned already, responsiveness to predicted probability essentially means responsiveness to prices and the inflation rate. Irrespective of the overall level of responsiveness observed in the experiment, or the difference between the 2x2 and 3x2 markets, a systematic difference in responsiveness across inflation rates within a market would suggest that buyers weren't appropriately accounting for the effect of the inflation tax. If buyers ignored the inflation tax, responsiveness would decrease as inflation rises, while if they focus too much on the inflation tax, responsiveness would increase with inflation. The fact that we see neither a rise nor a fall in responsiveness within either market suggests that buyers are – on average – correctly incorporating the inflation tax in with prices when making their visit decisions. It also implies that our comparative-static theoretical predictions for the effect of the inflation rate on *seller prices* could reasonably be expected to prevail in the experiment – as we have seen they do.<sup>24</sup>

as extremely high levels of loss aversion are required to match the amount of price inelasticity observed in the experiment: a loss-aversion parameter well above 12, as compared to values of 2 or 3 typically estimated from individual decision-making tasks. See Appendix E for illustrations of the effects of risk and loss aversion on predicted buyer visit behaviour.

<sup>23</sup>Pairwise tests between any two inflation rates within a market also yield no significant differences.

<sup>24</sup>For example, if buyer responsiveness to predicted probability had alternatively been systematically lower as inflation increased, simultaneous best-response by sellers might have implied no effect of inflation on prices, or even an increase with inflation.

## 6 Discussion

We examine the effects of the inflation tax with a theoretical and experimental analysis. Our theoretical model is the monetary version of Burdett, Shi and Wright's (2001) posted-price directed-search model. Sellers in a frictional market independently post prices, which are observed by buyers who then independently decide (a) which seller to visit, and (b) how much cash to hold. Holding cash is necessary in order to buy the seller's item, but is costly because of inflation. We show the model implies that rises in the inflation rate are associated with decreases in real prices and real production of the search good, at a rate that diminishes with inflation.

We test the model's predictions with an experiment using three inflation rates. Our results, which are quite stark compared to many lab experiments, are largely consistent with the model in both first-order effects (higher inflation leads to lower real prices, production and welfare) and second-order effects: the magnitude of the effect of a one-percentage-point rise in the inflation rate between 0% and 5% inflation on a given statistic varies from 2.5 to 11 times the corresponding effect between 5% and 30% inflation (see Table 3 for raw semi-elasticities and Table 6 for semi-elasticities estimated from regression models).<sup>25</sup> The effects we find persist as subjects become more experienced, with no economically meaningful variation across replications of the setting. Buyer behaviour also largely supports the model's comparative-static predictions.

Our results indicate that the impact of the inflation tax should not be underestimated, with even fairly low levels of inflation leading to significant changes in individual behaviour and market aggregates. This leads to an important implication. Although high levels of inflation are universally viewed to be harmful, it is also conventionally accepted that, if the inflation rate could be kept in the low single digits, and as long as changes could be predicted with some degree of accuracy, a society could live fairly easily under such a regime. Indeed, low positive levels of inflation are often viewed as beneficial in developed societies. Our results suggest that positive inflation – however low – entails non-negligible costs, which must be weighed against any benefits.<sup>26</sup>

We believe we have taken a small but worthwhile step toward quantifying the effects of the inflation tax in a controlled setting. We encourage other experimental work in this area. The clarity of our results makes us confident of their robustness to changes in experimental procedures and parameters, but future research might test this robustness by looking at either larger markets (more buyers and sellers) or alternative pricing protocols, such as random matching with bilateral bargaining (as Lagos and Wright (2005) did theoretically). Another avenue for future research would examine other channels through which inflation's effects could be felt. For example, the "hot potato effect" (Li, 1994; Lagos and Rocheteau, 2005; Ennis, 2009), by which a rise in inflation induces individuals to get rid of their money holdings faster by speeding up their trades or shopping more intensely, may be well-suited for experimental testing, due to the theoretical possibility that the effect could actually go in the other direction (as noted by Liu, Wang, and Wright (2011)) and the difficulty in finding direct evidence from field data. Still another extension would allow multiple channels through which money can affect the economy (e.g., both the inflation tax and the hot potato effect, or either of these combined with expectations of future macroeconomic variables), thus allowing for direct comparisons between channels.

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<sup>25</sup>In our exposition, we have concentrated on the effects of an *increase* in inflation. It is worth noting that – because we found little evidence of order effects (see Table 5) – conclusions about *disinflation* are equally valid from our results. For example, the effects of inflation falling from 5% to 0% are simply the reverse of those from inflation rising from 0% to 5%.

<sup>26</sup>Dutu, Huangfu and Julien (2011) show in another setting that low levels of inflation can have significant effects. They add inflation to Coles and Eeckhout's (2003) model of demand-contingent price posting and directed search, and find that under even an arbitrarily small positive inflation rate, Coles and Eeckhout's indeterminacy result disappears in favour of a unique equilibrium.

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## A Additional information about experimental procedures

The experiment has a 3-by-2 factorial design, with the inflation rate varied within-subjects over the values 0%, 5% and 30%, and the market (2x2 or 3x2) varied between-subjects. To reduce and control for order effects, we varied the ordering of the inflation rates between-subjects, using three of the six possible orderings (see Table 9). We chose the 2x2 market because it is the smallest market where both buyers and sellers face uncertainty about whether they will be able to trade. (Smallness is valuable in our experiment, since small markets allow us to collect more independent observations with a given budget for subject payments.) We chose the 3x2 market because it is one of the two next-smallest markets, the other being the 2x3 market. Both the 3x2 and the 2x3 markets have the added benefit of equilibria well away from the equal-split norm, as opposed to the 2x2 market whose equilibrium price of 10 when  $\tau = 0$  gives buyer and seller equal profits. However, the 2x3 market would have led to frequent rounds of negative profits for each buyer, and – since the likely high prices give buyers less opportunity to earn large positive profits in other rounds to offset the losses – a real possibility of overall negative payments to subjects. As usual in experiments, negative payments could not credibly be enforced, thus providing incentives for risk-seeking behaviour, especially by those subjects incurring early losses, hoping to get back above zero payments and knowing that further losses would be costless. Thus, we chose the 3x2 market over the 2x3 market.

Each session lasted for 54 rounds, split into three blocks of 18 rounds each, and with subjects facing a different inflation rate in each block. In a given round, all subjects in a session faced the same inflation rate. There were a

Table 9: Treatment and session information

Session	Market	Ordering of inflation rates	Number of		
			subjects	markets	matching groups
5	3x2	5–30–0	10	2	1
6	2x2	0–5–30	16	4	2
7	2x2	5–30–0	16	4	2
8	3x2	0–5–30	15	3	1
9	3x2	5–30–0	10	2	1
10	2x2	30–0–5	16	4	2
11	3x2	30–0–5	15	3	1
12	2x2	30–0–5	12	3	1
13	3x2	5–30–0	15	3	1
14	3x2	30–0–5	20	4	2
15	2x2	0–5–30	16	4	1
16	2x2	5–30–0	12	3	1
17	3x2	0–5–30	10	2	1
18	3x2	5–30–0	10	2	1

*Note: 4 pilot sessions not analysed in this paper.*

total of fourteen experimental sessions (not including four pilot sessions, with some differences in procedures and which we leave out of our data set), conducted between August 2012 and January 2013. Session size varied from two to four times the size of a market (8–16 for the 2x2 market and 10–20 for the 3x2 market). There were 193

subjects in all.

Subjects remained in the same role (buyer or seller) in all rounds, but the composition of the markets (containing two buyers and either two or three sellers) was randomly drawn in each round, so that a given subject was matched with different people from round to round; this was done primarily to lessen the likelihood of repeated–game effects like reputation building or dynamic collusion. Some larger sessions were partitioned into two independent “matching groups”, each double the size of a market. Matching groups were closed to interaction (i.e., individual markets were always subsets of a matching group). There was a total of 18 matching groups: 3 for each combination of market and inflation–rate ordering. No mention was made to subjects of the existence of these partitions; subjects were told only that they would be randomly assigned to markets in each round, not that some matchings never occurred.

The experimental sessions took place at MonLEE, Monash University’s experimental economics lab. Subjects were primarily undergraduate students from Monash University, and were recruited using the ORSEE web–based recruiting system (Greiner, 2004). No one took part more than once. The experiment was run on networked personal computers, and was programmed using the z–Tree experiment software package (Fischbacher, 2007); some sample screen–shots are shown in Appendix D. Subjects were visually isolated, and were asked not to communicate with other subjects except via the computer program.

At the beginning of a session, subjects were seated at desks with computers, and given written instructions (a sample is provided in Appendix C). The instructions were also read aloud to the subjects, in an attempt to make the rules common knowledge. Additionally, before the first round, a public announcement was made of the initial inflation rate, and it was announced that additional public statements would be made whenever the rate changed (and were made after rounds 18 and 36).

Each round began with both buyers and seller being reminded of the inflation rate, which was framed as an “interest rate” to subjects. Firms were prompted at this time to choose their prices, which could be any multiple of 0.05, between 0 and 20 inclusive. Prices and  $Q$  were framed to subjects as being measured in Australian dollars, though to be precise, they are measured in units of the general good and then converted for the purpose of payment to subjects (at the rate of one–to–one) at the end of the experimental session. The restriction of prices to  $[0, 20]$  reflects the fact that choosing a price outside this interval is weakly dominated; we simplified the decision situation by making such seller choices impossible rather than merely undesirable. The restriction to multiples of 0.05 is because Australia no longer circulates coins with denominations smaller than 5 cents.

After the sellers had entered their prices, buyers observed these prices and were prompted to choose which firm to visit. Within a round, the firms in a market were labelled as “Seller 1”, “Seller 2”, and in the 3x2 market, “Seller 3”, so that buyers could make clear which one they wanted to visit. These labels were chosen randomly and i.i.d. in each round, preserving anonymity and ensuring that labels could not be used as a coordination device across rounds. Buyers also chose their cash holdings at this time; these could also be any multiple of 0.05 between 0 and 20 inclusive. (Since 20 is the maximum price, there is no benefit to the buyer from a cash holding greater than this.) Once all buyers had made both of these decisions, the round ended and subjects received feedback. Firms were informed of both own and rival prices, how many buyers visited them, the quantity sold and profit. Buyers were informed of all prices, which firm each buyer visited, the quantity bought and profit.

At the end of the last round, subjects were paid, privately and individually. For each subject, two rounds from each block of 18 were randomly chosen, and the subject was paid in Australian dollars his/her earnings in those six rounds (rounded to the nearest multiple of 5 cents when necessary), plus a \$10 show–up fee. Subjects’ total earnings averaged just under \$50 and ranged from \$10 (for one subject) to \$102.10, for a session that typically lasted about 90 minutes.

## B Equivalence of the infinite–horizon model and one–shot experimental round

Here we demonstrate that our experiment implements the setting described in the model (Section 3), even though the former involved 54 independent instances of a one–shot setting, while the latter involved an infinite–horizon dynamic setting. In essence, each experimental round involves play of the first period of the infinite–horizon model, along with the beginning of the second period (the Walrasian market). The infinite–horizon model is truncated there for the experimental subjects, but finite–endpoint problems are avoided by our payment scheme and the quasi–linear specification of instantaneous utility for both buyers and sellers. Our payment scheme implicitly forces buyers and sellers to re–balance their cash holdings to zero at the end of the experimental round, as they could do in the model by buying or selling the general good at the beginning of the second period. Experimental payments are determined based on all actions up to the re–balancing. The forced re–balancing at the end of the experimental round does not constrain optimal behaviour in the model, since further buying and selling in the Walrasian market would still be possible (e.g., for buyers wishing to hold cash to buy the search good in the subsequent frictional market), and linear utility in the general good means that buying or selling in two steps rather than one in the sub–period does not affect lifetime utility. In the model, optimal behaviour in the continuation is assumed when deriving the solution, and the resulting continuation value is a component of lifetime utility. In the experimental round, we also assume optimal behaviour from the point of truncation on, but as shown below, we subtract off (a constant times) the continuation value given a zero cash holding from the lifetime utility when computing the subject’s monetary profit.

Following the notation in the paper, let  $W^b(z)$  and  $V^b(z)$  be the value functions for a buyer holding  $z$  units of cash in the Walrasian and frictional markets respectively. Let  $W^s(z)$  be the value function for a seller holding  $z$  in the Walrasian market, and let  $V^s(p)$  be the seller’s value function in the frictional market when choosing price  $p$ . Let  $\beta$  be the discount factor,  $\phi$  and  $\phi_{+1}$  be the prices of money in terms of the general good in the current and next periods respectively,  $Q$  be buyers’ reservation price for the search good, and  $T$  be the cash transfer to each buyer from the central bank. Define  $\Phi$  and  $\Omega$  to be the probability a seller and a buyer (respectively) are able to trade given buyers’ visit choices.

We now show equivalence between a round of the experiment and the infinite–horizon model, in the sense that the respective payoff functions are affine transformations of each other, for any  $\beta < 1$ , as long as (a) buyers and sellers begin with zero cash holdings, and (b) agents behave optimally in the continuation (i.e., decisions in the infinite–horizon model that take place after the round of the experiment is completed). Behaviour need not be optimal in those decisions in the infinite–horizon model corresponding to decisions in an experimental round. We show this equivalence first for sellers, then for buyers.

### Sellers

Consider a seller at the beginning of a period (i.e., in the Walrasian market) of the infinite–horizon model, initially holding  $z$  units of money. Suppose she chooses price  $p$ , and let  $\overline{W}^s$  be the resulting payoff function, assuming optimal continuation behaviour in all future periods, but not necessarily optimal behaviour in the current period. (This last point is our reason for using  $\overline{W}^s$  instead of  $W^s$ .) We have

$$\begin{aligned}
 \overline{W}^s(z, p) &= \phi z + \beta V^s(p) \\
 &= \phi z + \beta[\Phi W_{+1}^s(p) + (1 - \Phi)W_{+1}^s(0)] \\
 &= \phi z + \beta\Phi[\phi_{+1}p + \text{Max}_{\tilde{p}}\{\beta V_{+1}^s(\tilde{p})\}] + \beta(1 - \Phi)\text{Max}_{\tilde{p}}\{\beta V_{+1}^s(\tilde{p})\} \\
 &= \beta\Phi\phi_{+1}p + \phi z + \beta^2\text{Max}_{\tilde{p}}\{V_{+1}^s(\tilde{p})\}.
 \end{aligned}$$

In the experiment, sellers begin period 1 with zero units of money, so we have

$$\overline{W}_1^s(0, p) = \beta\Phi\phi_2p + \beta^2\text{Max}_{\tilde{p}}V_2^s(\tilde{p}) = \beta\Phi\phi_2p + \beta W_2^s(0). \quad (21)$$

On the right-hand side of (21), the second term is a constant, while the first term is  $\beta$  multiplied by the payoff function for sellers in a round of the experiment: the probability of selling a unit multiplied by the profit conditional on selling a unit. Thus, the seller payoffs in the infinite-horizon model and those in the experimental stage game differ only by an affine transformation.  $\square$

### Buyers

For a buyer initially with  $z$  units of money and choosing to hold  $\hat{z}$  in the Walrasian market, let  $\overline{W}^b$  be the resulting payoff function (as with sellers, assuming optimal behaviour in future but perhaps not in the present). Then,

$$\begin{aligned} \overline{W}^b(z, \hat{z}) &= \phi(z + T) - \phi\hat{z} + \beta V^b(\hat{z}) \\ &= \phi(z + T) - \phi\hat{z} + \beta[\Omega Q + \Omega W_{+1}^b(\hat{z} - p) + (1 - \Omega)W_{+1}^b(\hat{z})]. \end{aligned}$$

Note that

$$\begin{aligned} W_{+1}^b(\hat{z} - p) &= \phi_{+1}(\hat{z} - p + T) + \text{Max}_{\tilde{z}}\{-\phi_{+1}\tilde{z} + \beta V^b(\tilde{z})\} \\ \text{and } W_{+1}^b(\hat{z}) &= \phi_{+1}(\hat{z} + T) + \text{Max}_{\tilde{z}}\{-\phi_{+1}\tilde{z} + \beta V^b(\tilde{z})\}, \end{aligned}$$

so that

$$\begin{aligned} \overline{W}^b(z, \hat{z}) &= \phi(z + T) - \phi\hat{z} + \beta\Omega Q + \beta\Omega[\phi_{+1}(\hat{z} - p + T) + \text{Max}_{\tilde{z}}\{-\phi_{+1}\tilde{z} + \beta V^b(\tilde{z})\}] \\ &\quad + \beta(1 - \Omega)[\phi_{+1}(\hat{z} + T) + \text{Max}_{\tilde{z}}\{-\phi_{+1}\tilde{z} + \beta V^b(\tilde{z})\}] \\ &= \phi(z + T) - \phi\hat{z} + \beta\Omega[Q - \phi_{+1}p] + \beta\phi_{+1}(\hat{z} + T) + \beta \cdot \text{Max}_{\tilde{z}}\{-\phi_{+1}\tilde{z} + \beta V^b(\tilde{z})\} \\ &= \phi(z + T) - \phi\hat{z} + \beta\Omega[Q - \phi_{+1}p] + \beta\phi_{+1}(\hat{z} - z) + \beta\phi_{+1}(z + T) \\ &\quad + \beta \cdot \text{Max}_{\tilde{z}}\{-\phi_{+1}\tilde{z} + \beta V^b(\tilde{z})\} \\ &= \phi(z + T) - \phi\hat{z} + \beta\Omega[Q - \phi_{+1}p] + \beta\phi_{+1}(\hat{z} - z) + \beta W_{+1}^b(z). \end{aligned}$$

In the experiment, buyers begin period 1 with zero units of money, so we have

$$\overline{W}_1^b(0, \hat{z}) = \beta \left[ \Omega(Q - \phi_2p) - \left( \frac{\phi_1}{\beta} - \phi_2 \right) \hat{z} \right] + \phi_1T + \beta W_2^b(0).$$

That is,

$$\overline{W}_1^b(0, \hat{z}) = \beta [\Omega(Q - \phi_2p) - \phi_2i\hat{z}] + \phi_1T + \beta W_2^b(0). \quad (22)$$

(Recall that  $i$  is the nominal interest rate.) The expression inside the square brackets is the payoff function for buyers in a round of the experiment (the first term is the consumer surplus times the probability of being able to buy, and the second is the amount of the inflation tax), while the last two terms in that expression are constants. Thus, the buyer payoffs in the infinite-horizon model and those in the experimental stage game differ only by an affine transformation.  $\square$

## C Instructions from the experiment

Below are the instructions from the 2x2 treatment; the instructions from the 3x2 treatment are nearly identical and available from the corresponding author. Horizontal lines indicate page breaks.

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### Instructions

You are about to participate in a decision making experiment. Please read these instructions carefully, as the money you earn may depend on how well you understand them. If you have a question at any time, please feel free to ask the experimenter. We ask that you not talk with the other participants during the experiment.

This experiment is made up of 54 rounds. Each round consists of a simple computerised market game. Before the first round, you are assigned a role: buyer or seller. ***You will remain in the same role throughout the experiment.***

In each round, the participants in this session are divided into “markets”: groups of four containing a total of ***two buyers*** and ***two sellers***. ***The other people in your market will change from round to round.*** You will not be told the identity of the people in your market, nor will they be told yours – even after the session ends.

***The market game:*** In each round, a seller can produce up to ***one*** unit of a good, at a cost of ***\$0***. A buyer can buy up to ***one*** unit of the good, which is ***resold to the experimenter*** at the end of the round for ***\$20***. It is not possible to buy or sell more than one unit in a round. Sellers begin a round by choosing the prices of their goods, which must be entered as ***multiples of 0.05, between 0 and 20*** inclusive (without the dollar sign).

After all sellers have chosen prices, each buyer observes the prices of each of the sellers in their market, then chooses which seller to visit. If the two buyers in a market visit ***different*** sellers, then ***both*** buyers have the opportunity to purchase their seller’s item at that seller’s price. If both visit the ***same*** seller, then since the seller can only produce one unit, ***only one*** buyer will have the opportunity to purchase the item at that seller’s price.

In order to be able to purchase an item, ***a buyer must be carrying enough cash to cover its price.*** Buyers begin each round with ***no cash***, but they can choose to ***borrow*** from the bank when they are choosing which seller to visit. The amount they choose to borrow can be ***any multiple of 0.05, between 0 and 20*** inclusive. The bank charges ***interest*** on any amount borrowed. The total interest charged in a round is equal to the ***interest rate*** multiplied by the amount borrowed.

Examples:

- If the interest rate is 10% (= 0.10) and the amount borrowed is \$15.00, then the interest charge is  $0.10 * \$15.00 = \$1.50$ .
- If the interest rate is 20% (= 0.20) and the amount borrowed is \$5.00, then the interest charge is  $0.20 * \$5.00 = \$1.00$ .
- If the interest rate is 40% (= 0.40) and the amount borrowed is \$0.00, then the interest charge is  $0.40 * \$0.00 = \$0.00$ .

The interest rate is shown on everyone’s screens at the beginning of each round, and it may be ***zero or positive***. It is the same for all buyers in a round, but it may change from round to round. ***When the interest rate changes, an announcement will be made to all participants.*** Interest charges are

automatically deducted from the buyer's profit, so there is no need to borrow to pay interest. Sellers have no reason to borrow, so do not pay interest.

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**Buying and selling:** If you are a *seller*, then you are *able* to sell your item as long as *at least one* buyer (a) visits you, and (b) has enough cash to pay the price you chose. If no buyer visits you, or if the buyers who did visit did not borrow enough to pay your price, then you are *unable* to sell.

If you are a *buyer*, then:

- If you and the other buyer chose *different sellers*, then you are able to buy your seller's item as long as you borrowed enough money to pay the price.
- If you and the other buyer chose the *same seller*, and the other buyer *did not borrow enough* to pay the seller's price, then you are able to buy as long as you have enough money.
- If you and the other buyer chose the *same seller*, and *both of you* have enough money to pay the price, then each of you has a *50%* chance of being able to buy the seller's item at that price. One of you is chosen *randomly* by the computer to buy; the other buyer will be *unable* to buy.
- If you *did not borrow enough money* to pay your seller's price, then you will be *unable* to buy.

**Profits:** Your profit for the round depends on the round's result.

- If you are a *seller* and you are *able to sell*, your profit is the selling price.
- If you are a *seller* and you are *unable to sell*, your profit is zero.
- If you are a *buyer* and you are *able to buy*, your profit is \$20.00 minus the price you paid, minus the amount of interest charged (if any).
- If you are a *buyer* and you are *unable to buy*, your profit is zero minus the amount of interest charged (if any).

**Sequence of play in a round:**

- (1) The computer randomly forms markets made up of two buyers and two sellers, and displays the current interest rate on everyone's screen.
- (2) Sellers choose their prices.
- (3) Buyers observe the sellers' prices, then each buyer chooses which seller to visit and how much to borrow from the bank.
- (4) The round ends. If you are a seller, you are informed of: each seller's price, how many buyers visited you, quantity sold and profit for the round. If you are a buyer, you are informed of: each seller's price, which seller each buyer visited, your quantity bought and profit for the round.

After this, you go on to the next round.

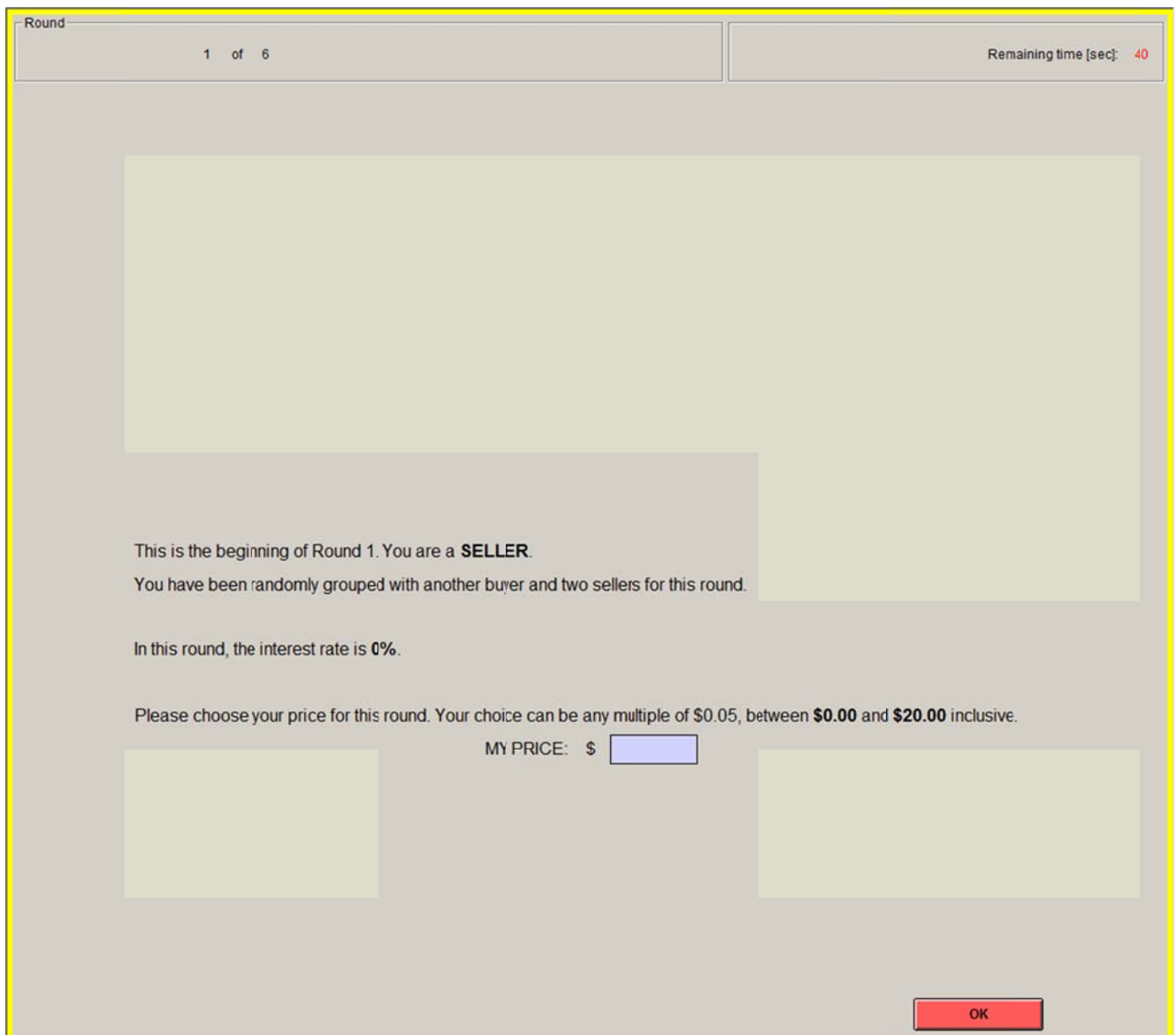
**Payments:** At the end of the experiment, *six* rounds will be chosen randomly for each participant. You will be paid your total profit from those rounds, plus an additional \$10 for completing the session. Payments are made privately and in cash at the end of the session.



## D Sample screen-shots from the experiment

Below are sample screen-shots from the experiment. They were taken during a test-run of the program; in the actual experiment the top line of each screen-shot would read “Round 1 of 54” rather than “Round 1 of 6”. Otherwise, they are typical of those seen by subjects in the 2x2 market with a 0% inflation rate. In these screen-shots, the seller shown chose a price of \$15.00, while the buyer visited a seller with a price of \$15.00 and chose cash holdings of \$16.00 (more than the necessary amount, but at no cost since inflation is zero). Both buyer and seller were able to trade. Screen-shots from other cells are available from the corresponding author upon request.

Seller decision screen:



Round

1 of 6

Remaining time [sec]: 40

This is the beginning of Round 1. You are a **SELLER**.  
You have been randomly grouped with another buyer and two sellers for this round.

In this round, the interest rate is 0%.

Please choose your price for this round. Your choice can be any multiple of \$0.05, between **\$0.00** and **\$20.00** inclusive.

MY PRICE: \$

OK

Buyer decision screen:

Round 1 of 6

Firm 1 has chosen a price of **\$15.00**.  
Firm 2 has chosen a price of **\$12.00**.

Please choose which of the sellers you will visit.

Remember that if you are the only buyer to visit a seller, then you will definitely be offered a unit to buy. If you and the other buyer visit the same seller, each of you has a 50% chance of being offered a unit to buy.

I CHOOSE TO VISIT  FIRM 1  
 FIRM 2

Please also choose how much cash you will borrow from the bank. Your choice can be any multiple of \$0.05, between **0.00** and **\$20.00** inclusive.

No interest is charged on the amount you borrow.

Remember that if you don't borrow enough money to pay the price of the good, you will be unable to buy.

I WILL BORROW: \$

OK

Seller feedback screen:

Round	1 of 6	Remaining time [sec]: 16
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History of your past outcomes:

Round	Interest rate (%)	Your cost of production (\$)	Your price (\$)	Other firm price (\$)	Number of buyers visiting you	Quantity you sold	Your profit (\$)
1	0	0.00	15.00	12.00	1	1	15.00

THIS ROUND'S RESULTS:

You chose a price of **\$15.00**.

The other seller chose a price of **\$12.00**.

You were visited by **ONE buyer**, with **ONE** able to afford your item.

So, you were **ABLE** to sell your item.

You sold your item for a price of **\$15.00**, and the cost of producing it was **\$0.00**.

Your profit for the round is **\$15.00**.

OK

Buyer feedback screen:

Round						Remaining time [sec]: 16			
1 of 6									
History of your past outcomes:									
Round	Interest rate (%)	Firm 1 price (\$)	Firm 2 price (\$)	Firm you visited	Firm other buyer visited	Amount you borrowed	Quantity you bought	Selling price	Your profit (\$)
1	0	15.00	12.00	1	2	16.00	1	15.00	5.00

THIS ROUND'S RESULTS:

Seller 1 chose a price of **\$15.00**.  
Seller 2 chose a price of **\$12.00**.

You chose to visit **Seller 1**, and to borrow **\$16.00** from the bank. The other buyer chose to visit **Seller 2**.  
You were **ABLE** to buy an item.

You paid a price of **\$15.00** for the item, and you resold it for **\$20.00**.  
Your profit for the round is **\$5.00**.  
You returned **\$16.00** to the bank.

OK

## E Can risk aversion or loss aversion explain buyer visit choices?

Two features apparent in Figure 5 (showing predicted and observed buyer visit choices) are (1) fairly substantial under-responsiveness to price in the 2x2 market, and (2) slight under-responsiveness in the 3x2 market. We look here at two potential explanations for these results: risk aversion and loss aversion.

Both risk aversion and loss aversion, from an intuitive standpoint, seem capable of explaining under-responsiveness to price. Consider the two buyers in a 2x2 market, and suppose they face a pair of prices low enough that staying home is dominated, and unequal but close enough together that the symmetric equilibrium in visit choices involves mixed strategies. In these circumstances, each buyer must choose between two lotteries. For example, for Buyer 1, visiting Seller 1 yields a large prize (the profit from buying from Seller 1) or a small prize (the non-positive profit from being unable to buy), with the latter's probability equal to the probability of Buyer 2 also visiting Seller 1, times one-half (the probability Buyer 2 is randomly chosen to buy in case both visit the same seller).

It is easy to show that under these conditions, and with any utility function that is increasing in money payment, the probability of visiting the low-priced seller will be greater than that of visiting the high-priced seller. This means that visiting the low-price seller means a higher potential profit (if the buyer is able to buy), but a lower probability of getting that profit. The high-price seller offers a lower potential profit, but a higher chance of getting it. Under risk aversion (or more precisely, decreasing marginal utility of money), the relative benefit of the higher potential profit from the low-price seller decreases, so that – other things equal – the high-price seller becomes more attractive, compared to the risk neutral case. Then the probability of choosing the high-price seller must adjust upwards to keep buyers indifferent between them in a symmetric equilibrium.

Now consider a buyer in the same situation who is loss averse (Kahneman and Tversky, 1979) – that is, he dislikes losses more than he likes equal-sized gains – but otherwise does not avoid risks. Under a positive inflation rate, the profit from being unable to buy will be strictly negative (rather than nil under zero inflation). Faced with the trade-off we've discussed (low probability of a high profit versus high probability of a low profit), a loss-averse buyer will be more sensitive to the higher probability of a loss when visiting the low-price seller, so – other things equal – the high-price seller becomes more attractive, compared to the loss neutral (i.e., expected-profit maximising) case. Again, the probability of choosing the high-price seller must adjust upwards.

In Figure 6, we illustrate these intuitive arguments with the use of reliability diagrams similar to the ones in Figure 5. Like the earlier figure, these diagrams concern buyer visit probabilities: in particular, the probability of visiting Seller 1. (The results are nearly identical for the other sellers.) Unlike the earlier figure, though, we are not comparing theoretical probabilities with observed frequencies. Instead, we compare theoretical probabilities under risk neutrality with theoretical probabilities under a particular model of risk aversion. That makes these diagrams directly comparable to those in Figure 5, in the sense that if all of the real buyers had the utility function assumed in one of the diagrams in Figure 6, they would show the same degree of responsiveness to the predicted probability in both figures.

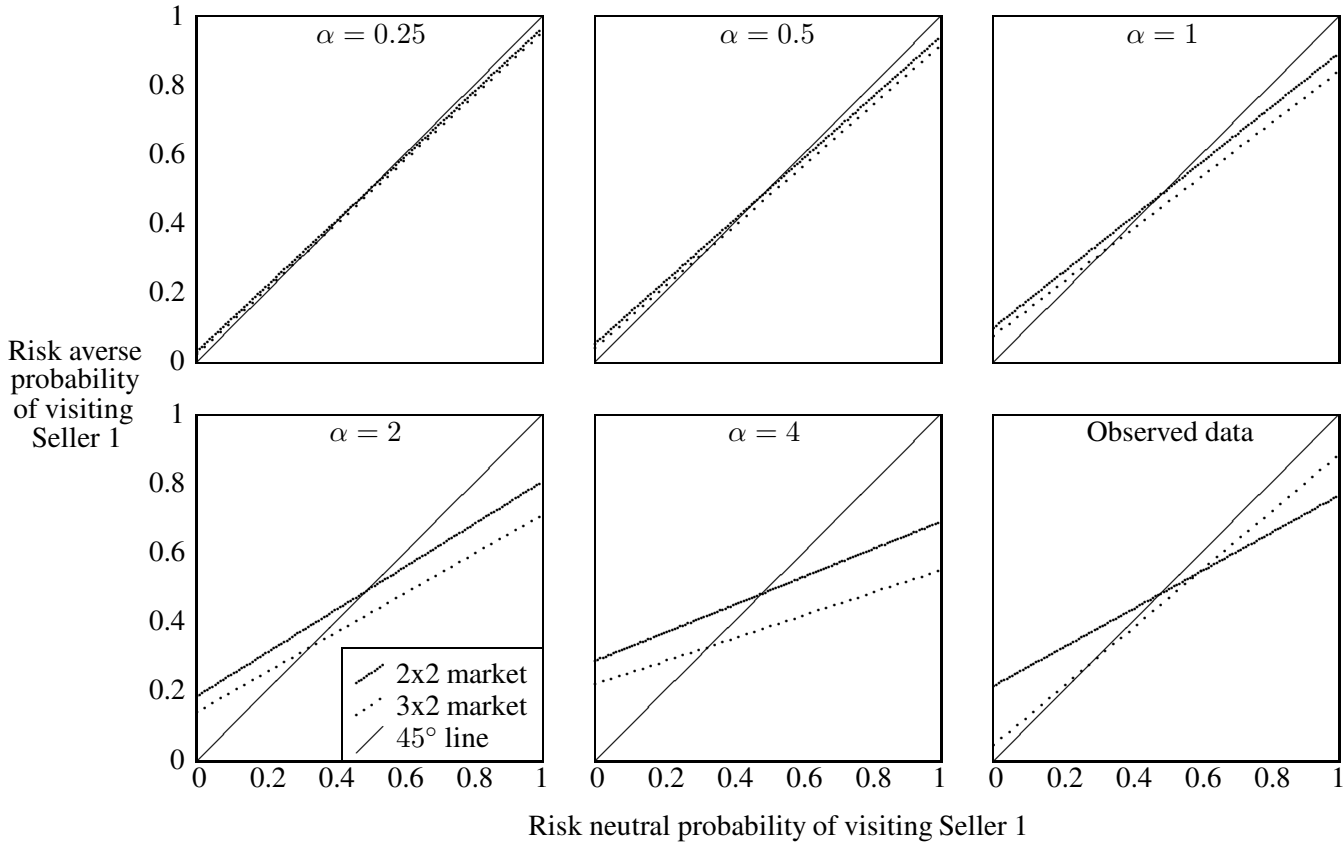
The top-left panel of Figure 6 shows the OLS trend lines that would obtain in the 2x2 and 3x2 markets (pooling over inflation rates) if all buyers had the utility function  $u(x) = \frac{1}{1-\alpha}(10+x)^{1-\alpha}$ , where  $x$  is money profit and  $\alpha = 0.25$ ; this is essentially a constant-relative-risk-aversion utility function with coefficient  $\alpha$ , except for the addition of 10 to profit.<sup>27</sup> The next four panels use the same functional form for utility, but different values of  $\alpha$ :

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<sup>27</sup>The minimum profit a subject can earn in a round is -6, so adding 10 guarantees that utility is defined. Under standard expected-utility theory, the subject's wealth should be in the utility function instead of a constant 10; however, Andersen et al. (2011) report evidence that subjects fail to integrate their experimental income with their wealth outside the lab, and thus in a sense act as if their outside wealth is much lower than it actually is.

0.5, 1 (i.e.,  $u(x) = \ln(10 + x)$ ), 2 and 4; the range from 0 (risk neutrality) to 4 covers the values typically estimated from the lab and the field (e.g., Beetsma and Schotman, 2001; Deck et al., 2008; Harrison and Rutström, 2008; Dave et al., 2010; Dohmen et al., 2011). The final panel shows the corresponding trend lines for the observed data (the same data as in Figure 5, but pooled over inflation rates).

Figure 6: Buyer visit probabilities – risk neutral vs. CRRA with parameter  $\alpha$  (OLS trends, pooled inflation rates)



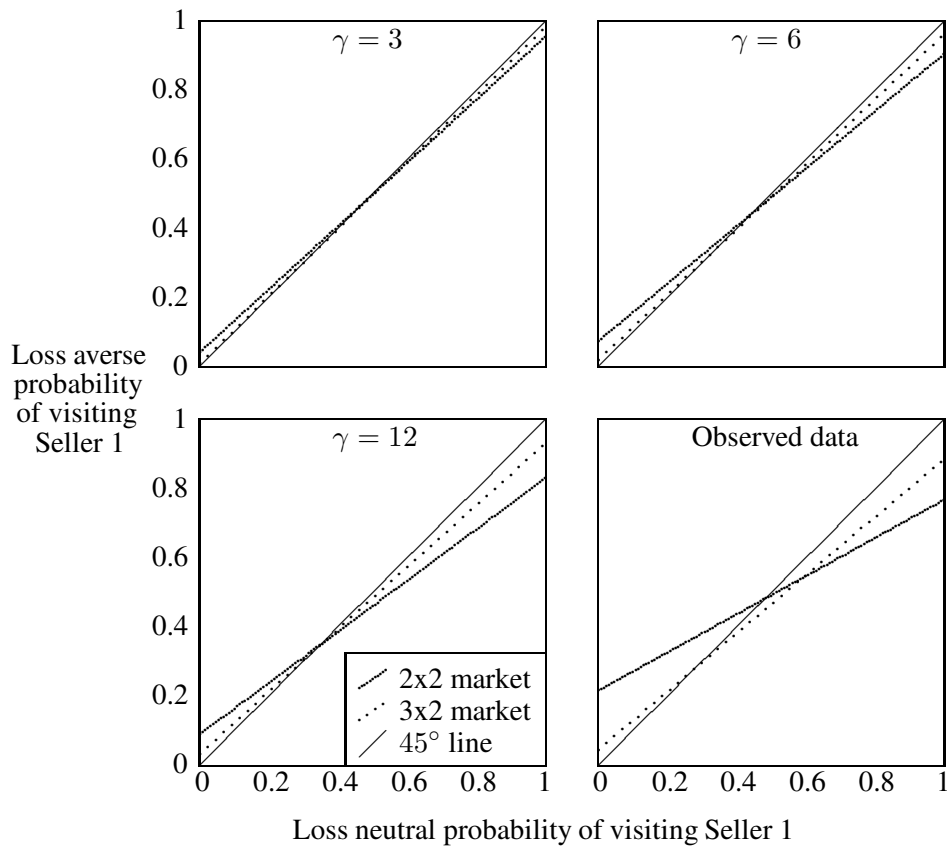
Consistent with intuition, risk aversion leads to less responsiveness to predicted probability, and equivalently less price elasticity; moreover, the effect gets larger as  $\alpha$  increases. However, for a given  $\alpha$ , the effect is actually slightly *larger* in the 3x2 market than in the 2x2 market, whereas the real subjects showed substantially *less* under-sensitivity to price in the 3x2 market. Thus, risk aversion has at best mixed success in characterising the price under-sensitivity we observe in the experiment.

We move to loss aversion. Figure 7 is similar to Figure 6, but these reliability diagrams are based on subjects who are loss averse. Specifically, they are assumed to have a linear utility-of-money function away from the origin, but a possible kink at the origin, so that the slope for negative values is  $\gamma \geq 1$  times that for positive values.<sup>28</sup> The top-left panel sets  $\gamma = 3$ , a value in the neighbourhood of those commonly estimated from individual decisions (e.g., Tversky and Kahneman, 1991; Camerer, 2005; Abdellaoui, Bleichrodt and L'Haridon, 2008). The next two panels use higher values of  $\gamma$  (6 and 12), while the last panel again shows the observed data.

As with risk aversion, loss aversion has mixed success in characterising the price under-sensitivity we observe

<sup>28</sup>Loss aversion is one part of Kahneman and Tversky's prospect theory; other parts include diminishing marginal sensitivity to both gains and losses, and non-linear weighting of probabilities. Though the parts of prospect theory are often taken together, there is no logical reason why they need to be, and it is certainly true that loss aversion on its own does not entail any of the other parts. We assume in this exercise that subjects are loss averse, but we leave out the other parts of prospect theory.

Figure 7: Buyer visit probabilities – loss neutral vs. loss averse with parameter  $\gamma$  (OLS trends, pooled inflation rates)



in the experiment. As our intuition suggested, loss aversion leads to lower price elasticity, and it decreases further as  $\gamma$  increases. Moreover, holding  $\gamma$  constant, the size of the effect is larger in the 2x2 market than in the 3x2 market, as we had seen in the experiment. However, while loss aversion captures the qualitative effects seen in real buyer behaviour, it performs poorly in a quantitative way. Even extreme levels of loss aversion ( $\gamma = 12$ ) entail a degree of under-responsiveness substantially less than what was actually observed. Thus, while loss aversion has more success than risk aversion in explaining these results, it still falls a bit short.