Currency competition, Monetary policy and Transaction costs: theory and experiments *

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Abstract

We study competition between an inflation-prone currency whose supply expands via central bank transfers, say the Dollar, and a fixed-supply currency, say Bitcoin, using a model *à la* Kareken-Wallace, but with currency-specific transaction costs. Absent costs, a multiplier in the Dollar supply leads not only to higher Dollar prices across time but also to a crowding-out effect of Bitcoin, an increase in the Dollar trade share, and an increase in Bitcoin prices. Transaction costs can undo the montary policy effect on the trade share, crowding out the Dollar, but amplify the multiplier effect on Dollar prices. We study all four treatments in theory and show that the predictions hold in a laboratory environment in a group experiment with student subjects.

key words: currency competition, dominant currency, transaction costs, crowding out of currency, inflation, monetary policy

1 Introduction

How does within-country competition of Dollars with Bitcoin as a medium of exchange affect the Federal Reserve's capacity to steer Dollar prices? (How) Does monetary policy affect the Dollar trade share, i.e. the share of all goods purchased with Dollars as opposed to Bitcoin? How do transaction costs affect monetary policy effectiveness and trade shares? We study these questions in theory and in the lab.

Here Bitcoin stands representative for a currency that is an alternative medium of exchange next to the Dollar in an economy, but its supply is not governed by the same central bank. Moreover, in our experiment, we assume that the Bitcoin supply is fixed over time. We are interested in how economic agents and subjects in the lab react to monetary policy if there exists an alternative medium of exchange against which sellers can decide to sell goods and buyers can decide to use for goods purchases versus savings.

As our main contribution, we show both in theory and in the lab that if the central bank multiplies every Dollar in the economy overnight by a factor $m > 1$, monetary policy is still effective when Dollars

*We dedicate this paper to our coauthor Jasmina Arifovic who sadly passed away before its completion. While she made substantial contributions to the earlier stages of the project, the views ultimately expressed in the paper may only be attributed to the remaining two authors. We thank our excellent research assistants Ibrahim Abuallail, Liang Diao, and Will Ho. Our experiment has been pre-registered on the AEA RCT registry under project number AEARCTR-0009274 and has been granted ethical approval by the Research Ethics Committee at Simon Fraser University under project number 2013s0789. Financial support from the Canadian Research Chair program and the Faculty of Economics & Business of the University of Amsterdam through the Research Priorities Area (RPA) 'Complex Human Systems Lab.' is gratefully acknowledged

compete with Bitcoin for usage. Dollar prices increase. However, in top of that, the central bank monetary policy increases the Dollar trade share, i.e. the share of goods sold for Dollars versus Bitcoin, and also leads to an increase in the Bitcoin price through a scarcity effect. Further, the Bitcoin price in Dollars (exchange rate) grows at the rate of the Dollar multiplier. Overall, Dollar monetary policy indirectly works as Bitcoin monetary policy. As the second main contribution, though, transaction costs can undo or amplify Dollar monetary policy. When sellers allocate goods to the Bitcoin-or Dollar market, they try to undo transaction costs in anticipation of becoming a buyer in the next period, selling for the currency at which they prefer to buy next. As a consequence, the Dollar trade share collapses, since we model asymmetric, currency specific transaction costs, that are increasing in the quantity of goods bought in Dollars. For buyers, on the other hand, the anticipation of changes in the trade share wuth implications for intertemporal costs can amplify the Dollar monetary policy such that with transaction costs, Dollar prices rise even faster than without transaction costs.

Despite its omnipresence in the modern economic landscape, currency competition for payments between two media of exchange, say the Dollar and Bitcoin, has been surprisingly under-researched. This topic has gained renewed importance with the rise of alternative monies, such as (central bank) digital currencies and cryptocurrencies, which challenge the dominance of traditional, national fiat currencies. Currency competition has the potential to alter the effectiveness of traditional monetary policy channels used by central banks to target inflation. Vice versa, central bank monetary policy and currency-specific transaction costs may affect the way currencies compete for usage or adoption in goods transactions. In this paper, we study in theory and in the lab how supply-oriented Dollar monetary policy and currency-specific transaction costs impact the way the Dollar competes with an alternate central bank -independent currency, say Bitcoin.

Traditional quantity theory of money (Friedman) for one currency teaches how changes in the Dollar supply or output pass through into the Dollar price, and the Dollar velocity. With two competiting currencies in the economy, these relationship no longer hold as clearly, since the agents can choose the currency they want to use for transactions or against which to sell their goods. The theoretical results in Schilling and Uhlig (2019a) show, that Dollar monetary policy can pass through into the Bitcoin price, potentially lessening the effect on the Dollar price. The results in (Schilling and Uhlig, 2019b) show that currency-specific transaction costs on payments can impact the dominance of one currency over the other by altering by altering the quantity of goods transacted in one currency versus the other.

Building on the theoretical frameworks in (Kareken and Wallace, 1981; Manuelli and Peck, 1990b; Schilling and Uhlig, 2019a,b), we develop a theoretical framework of currency competition with monetary policy, or transaction costs, or both, which we then test using a lab experimental design. The aim of this paper is to test how changes in the Dollar supply and transaction costs pass through not only into the Dollar price, and velocity, but also the quantity of goods traded for Dollars versus Bitcoin, the Bitcoin price, Bitcoin velocity, and the Bitcoin exchange rate. Ultimately, we are interested in how Dollar monetary policy and transaction costs affects crowding out, or the dominance of one currency over the other, where dominance means the quantity of goods traded in each currency. We believe this is an important measure since trade volume in either currency is a real measure, and is affected by the willingness of both sides of the market - buyers and sellers- to trade at a given price, whereas prices can be substantially perturbed by changes in the Dollar supply, a reaction in the Bitcoin and Dollar velocity, and sellers' willingness to trade against particular currency.

In this paper, the Dollar should be understood as a represenative of a central bank controlled money that can be flexibly steered up and down regarding its supply. In contrast, Bitcoin should be understood

as a placeholder of a currency with unflexible supply. That is, either the supply cannot be changed or changes in a foreseeable way, as is the case for Bitcoin and its protocol. In the case of transaction costs, the Dollar is a represenative of a currency for which the transaction costs increase in the intensity with which the currency is used. For instance, the costs of privacy loss may increase in the usage of unanonymous money since online retailers or banks learn more about their customers, the more the customers transact. Bitcoin, in the context of transaction costs, stands as a representative of a (semi)anonymous currency where transaction costs apply but in a proportional form to total transactions, as may be the case with mining fees.

In our economy, buyers and sellers can simultaneously interact in two currency-specific goods markets, denominated in either Dollars or Bitcoin. The buyers and sellers alternate in each role across time, which prevents the double coincidence of wants and creates a role for money as a medium of exchange. The sellers are endowed with an exogenous amount of perishable chips packages, the single consumption good in the economy. The agents do not enjoy consuming chips in periods in which they are sellers which prevents them from consuming their endowment, and creates a motive for trade in exchange for Bitcoins or Dollars. The sales proceeds allow them to buy chips packages in the next period when they are buyers.

In the lab, we study four treatments regarding Dollar monetary policy and transaction costs. In a first, benchmark treatment, there is neither Dollar monetary policy nor transaction costs. In that treatment, Dollar and Bitcoins are perfect substitutes. In a second treatment, we implement Dollar monetary policy without imposing transaction costs. We let the central bank grow the subjects' Dollar balances over time while we leave the Bitcoin quantity unchanged. In a third treatment, we impose currency-and quantity specific transaction costs for Bitcoin and Dollar purchases, but leave Dollar monetary policy mute, keeping the Dollar supply stable as the Bitcoin supply. In a fourth treatment, we combine Dollar monetary policy with transaction costs.

Investigating currency competition using field data is particularly challenging. Naturally occurring data are inherently noisy since many more than two currencies may co-exist, and are subject to distinct regulatory frameworks, affecting currency adoption and circulation. Comprehensive micro-level transaction data are usually unobserbable and trading in Bitcoin and other alternative currencies has primarily been limited to clandestine activities or countries with a poor track record of data collection. Given this lack of empirical data, the laboratory appears as an appealing environment to explore our research question. The underlying model that disciplines the lab economies features a continuum of equilibria where quantities, prices or both can adjust to the introduction of transaction costs or the increase of the money supply. This 'anything-goes' result provides an ideal playground for an exploratory endeavor where we intend to 'let the laboratory speak.' In our experiment, groups of participants trade a single consumption good across two currency-specific goods markets, denominated in Bitcoin or Dollars within a continuous double auction (CDA) market mechanism. In a two-by-two design, we consider markets with and without currency-specific transaction costs and economies with and without a central bank that inflates the quantity of Dollars in each period. We emulate strong impatience in the game so that currencies should compete for being the medium of exchange rather than a store of value since savings is discouraged.

Our results are as follows. The introduction of Dollar monetary policy by increasing the Dollar quantity increases both the Dollar and the Bitcoin price of goods relative to the benchmark case without monetary policy. There is strong Dollar inflation across trading rounds but no Bitcoin inflation. The number of goods traded against Dollars rises sharply relative to goods traded for Bitcoin (crowding out of Bitcoin).

However, also the Dollar savings increase whereas Bitcoin savings rates go down across rounds, implying an increase in the Bitcoin velocity in response to the increasing Dollar supply. The impact on the Dollar velocity is uncertain. In addition, the Bitcoin exchange rate rises fast across trading rounds, i.e. Bitcoin becomes more valuable against the Dollar.

Second, the introduction of transaction costs on both Bitcoin and Dollar purchases without monetary policy increases both the Bitcoin and the Dollar price of goods relative to the benchmark without costs. The quantity of goods traded against either currency is unchanged. The savings rates in Dollars, Bitcoins, and the Bitcoin exchange rate are unaltered.

Third, when adding transaction costs on the monetary policy scenario, the transaction volume in Dollars crashes down, meaning there are fewer goods purchased in Dollars versus Bitcoin (crowding out Dollars). Essentially the transaction costs undo the increase of the Dollar's market share regarding purchases. Adding transaction costs on the monetary policy scenario additionally increases both the Bitcoin and the Dollar price, and preserves the strong inflation on the Dollar. The savings rates in Dollar remain unchanged whereas the savings rate in Bitcoin declines, and falls below the benchmark without transaction costs or monetary policy. Thus, adding the transaction costs to monetary policy increases the Bitcoin velocity.

We conclude, in a world in which transaction costs on payments seem to become inevitable due to privacy loss, value added tax, and the risk of identity theft, Dollar monetary policy is not a straight forward tool when agents can evade the Dollar by making purchases using Bitcoin. The experimental results show that under currency competition, an increase in the Dollar supply without adding transaction costs benefits the Dollar with regard to its dominance, i.e. total transaction volume, and preserves, but possibly weakens the traditional monetary policy channel between the Dollar supply and the Dollar price. However, transaction costs have strong effects on the economy, and weaken the Dollar's role as the dominant medium of exchange, by lowering the Dollar trade volume and amplifying Dollar inflation.

The rest of the paper is organized as follows. After discussing the related literature, Section 2 presents the experimental environment, Section 6 discusses the results and Section 7 concludes.

1.1 Literature

Unlike in SU, where there exists a continuum of consumption goods, our model features only one consumption good. We choose a single good instead of multiple goods, because trading many different goods at different prices would result in an excessively high cognitive load for the participating subjects. To study currency substitution under transaction costs, we implement transaction costs as quantity- and currency specific. Specifically, transaction costs may vary not only by currency but also in the quantity of goods purchased with one currency, whereas in (Schilling and Uhlig, 2019b), there exists a variety of consumption goods, and the transaction costs vary with the good but are constant in the purchased quantity of a good.

Our work lies at the cross-road between theoretical models of currency competition and the experimental finance literature exploring the use of money in the laboratory. The theory front has grown in the wake of the well-known result of Kareken and Wallace (1981) who establish that when two fiat monies coexist in a free-trade environment, the exchange rate between the two is indeterminate and pinned down by the initial price levels. Related contributions include Manuelli and Peck (1990a), the turnpike models (see, e.g., Manuelli and Sargent 2010 for an discussion), and the earlier generation of monetary search models *à la* Kiyotaki and Wright (1989); see, e.g., Camera and Corbae (1999). These models study

the transition from barter to currency-based systems where an intrinsically worthless object becomes a medium of exchange in a world with fixed prices, frictions such as storage constraints and decentralized trades. Yet, the theoretical literature on currency competition has remained surprisingly scare.

The closest to our theoretical environment is the model of Camera et al. (2004) where one currency carrying a 'bad' money that carries a purchasing power risk through stochastic taxation co-exists with a 'good' money that does not, mimicking situations of Dollarization in countries with impaired financial systems. Like in our model, multiple equilibria exist, and agents tend to spend the 'good' money in the presence of trade frictions when the risk of the 'bad' money is relatively high, but may also choose to spend the 'bad' money otherwise.

The rise of crypto-currencies has renewed the interest in models of money search and currency competition.[1] Fernández-Villaverde and Sanches (2019) develop a frictionless model of competition between privately issued, decentralized monies. In such a model, Rahman (2018) shows how the unconstrained issuance of these decentralized monies prevents the Friedman rule from implementing the social optimum. Zhu and Hendry (2018) transpose a model of technology adoption with increasing returns to scale to the competition between the Dollar and an E-money, possibly a CBDC. They show that, in an inflationary environment, agents may switch to trading in E-money, which weakens the control of the CB over the Dollar inflation. Garratt and Wallace (2018) study an overlapping-generation (OLG) economy with competing currencies but absent monetary policy. The underlying framework of our experiment builds upon the model of Schilling and Uhlig (2019a), which is a stochastic and infinite-horizon extension of Kareken and Wallace (1981) where competition takes place between the centrally controlled currency (say, Dollar) and a decentralized currency (say, Bitcoin). In a deterministic version of this framework, Schilling and Uhlig (2019b) introduce currency-specific transaction costs.

This class of models features multiplicity of equilibria, so that 'anything goes' in theory: depending on initial conditions, trade may occur in only one of the two currencies, or the market share of each currency is anywhere between these two nested cases, depending on whether relative prices or quantities adjust in the presence of transaction costs or monetary policy. When theory results in this indeterminacy, there is a long tradition of using either learning models or laboratory experiments as selection device to help discriminate between multiple equilibra.[2] Within the context of the model of Kareken and Wallace (1981), Marimon et al. (1990) study classifiers systems and Sargent (1993) shows that the exchange rate does converge to a constant value pinned down by initial beliefs by using a stochastic approximation algorithm. Arifovic (1996) combines experimental evidence with simulations of genetic-algorithm learning and shows that the exchange rate persistently fluctuates in both settings, contrary to the theoretical prediction. When introducing seignorage, Arifovic (2001) shows that this learning mechanism results in the currency that finances the highest deficit to be driven out, again in sharp opposition to the perfect-foresight results. Given the discrepant conclusions under learning, the lab constitutes an empirical test of the validity of these learning theories, and the relevance of the selected equilibria. Therefore, our paper is closely related to the literature on experimental tests of monetary models (see Duffy et al. 2016, Section 4.1 for a survey).[3] While the framework of Kareken and Wallace (1981) has been renewed by the

[1] We abstract here from the somewhat vast literature on crypto-currencies in general (see, *inter alia*, Lee 2015; Böhme et al. 2015), the valuation of crypto-currencies (see, e.g., Bolt and Van Oordt 2020; Van Oordt 2024 and the literature herein, concentrated on models of rational bubbles), or the potential vulnerability and practical challenges associated to the blockchain technology underlying crypto-currencies (see, e.g., Huberman et al. 2019). The framework derived from Schilling and Uhlig (2019a,b) that we develop in this paper proxies a world where those issues have been resolved and do not prevent the use of a crypto-currency, both as a mean of exchange and as a speculative holding.

[2] See the discussion in Lucas Jr (1986), the survey of Camerer (2003) for application of this approach to games, and earlier contributions of, *inter alia*,Marimon and Sunder (1993, 1994); Van Huyck et al. (1990).

[3] This line of research is part of the (much) broader finance literature that investigates asset (mis)pricing and excess volatility

theoretical contributions of Schilling and Uhlig (2019a,b) for an application on competition between fiat monies and crypto-currencies, learning or experimental implementations within this context has yet to take place, and our experiment is the first attempt to do so. Experiments within money-search models to study the emergence of money as a medium of exchange are much more common; see, *inter alia*, Brown (1996); Duffy and Ochs (1999, 2002); Camera et al. (2003); Camera and Casari (2014) on experimental tests of the model of Kiyotaki and Wright (1989). Duffy and Puzzello (2014a) test the model of Lagos and Wright (2005), which is tractable and generates endogenous prices, and find that money is welfare-improving, while the theory predicts no impact on welfare. Duffy and Puzzello (2014b) additionally show that prices tend to increase proportionally to the increase in the quantity of money, in line with the quantity theory of money. Jiang et al. (2024) use finite-horizon experimental economies to investigate the effect of using fiat currency on welfare in various settings and show that the results are consistent with the theory.

Our study also relates to the literature on multi-country experiments. The study of Noussair et al. (2007) considers a three-country-three-currency experimental environment to study general equilibrium dynamics but does not investigate currency competition. Ding and Puzzello (2020) set up an experiment based on the model of Lagos and Wright (2005) with two countries and two currencies to study exchange frictions; see also the related study of Jiang and Zhang (2018). Finally, a related literature on the use of lab experiments for monetary policy design is reviewed in Cornand and Heinemann (2019) but these studies focus on expectations, usually within New Keynesian models. To the best of our knowledge and at the time of writing, none of these papers focuses on currency competition, its implication for monetary policy implementation or how equilibrium selection is affected by trade frictions, as is the case in the models of Schilling and Uhlig (2019a,b).

Earlier accounts of currency competition come from Medieval Europe and early modern England up until the eighteenth century or the U.S. in the nineteenth century under the bimetallic standard. The so-called Gresham's law that 'bad money drives out good' emerged in this context: when two currencies are in circulation and have the same value by law, the currency with lower intrinsic value (bad money) tends to be used more in transactions, while the currency with higher intrinsic value (good money) is hoarded or removed from circulation.[4] However, many empirical exceptions to this law have been documented and disagreements persist as to its interpretation. The alternative sometimes referred to as the Thiers' law that 'good money drives out bad' has also been formulated, for instance in post WWI-Europe where the bad monies refer to the currencies of countries subject to hyperinflation, and the good monies to those offering a stable store of value (League of Nations, 1946; Bernholz, 1989). While fascinating, this early line of research offers limited insights into to the competition between fiat and alternative monies in today's financial world.

2 The model

The experiment is based on a perfect foresight version of the currency competition model of Schilling and Uhlig (2019a) (hereafter, SSBE) and the currency substitution model with transaction costs in Schilling and Uhlig (2019b) (hereafter, SU). While SSBE also implement monetary policy, this paper differs with regard to the implementation of monetary transfers since we use a multiplier so that transfers to agents,

in experimental markets; see Noussair and Tucker (2013); Weitzel and Kirchler (2023) for reviews and, e.g., (Haruvy and Noussair, 2006; Haruvy et al., 2007; Kopányi-Peuker and Weber, 2021) for examples.

[4] See, e.g., Fetter (1932); Rolnick and Weber (1986); Greenfield and Rockoff (1995). In a fascinating piece, Radford (1945) wrote an account of the 'market developments' in a prison camp during WWII after his own experience as a prisoner and economist. His account is in line with Gresham's law: the 'bad money' (cigarettes of poor quality) drove out the 'good' (cigarettes of premium quality) as the prisoners' preferred medium of exchange and unit of account.

here, can be asymmetric and grow in proportion to their Dollar balances. SU also implement transaction costs. However, that model features infinitely man goods, transaction costs per good in either currency are quantity independent, and costs are monetary, added on the purchase price like a tax. Here, we only feature one good, as in SSBE, but transaction costs for one currency are quantity dependent, increasing in the number of goods purchased in that currency whereas the other cost applies flat. Further, we differ from the implementation there since here costs incur in the form of frictions, actling like an endogenous supply shock. Moreover, unlike in SSBE and SU, here the sellers preallocate packages to currency markets, and cannot be redistributed as trade opens whereas in SSBE and SU, every goods is simultaneously for sale against Bitcoin and Dollars. While SSBE is a stochastic model, here, we have perfect foresight as in SU.

We consider an infinite-horizon economy with discrete time $t = 1, 2, \ldots,$. There is a single, perishable consumption good, which we call packages of "chips."

Media of exchange Buyers can purchase chips packages with either of two competing currencies. We follow SSBE, by calling these currencies Bitcoin and Dollars in the theory model. In the experiment, however, we call the currencies "Currency A" for Dollars and "Currency B" for Bitcoin to avoid any kind of predisposition the subjects may have towards Bitcoins or Dollars. In the model, the name "Bitcoin" should be thought of as a placeholder for currencies for which no institution such as a central bank exists that could manipulate its supply up or down to impact the price level.[5] The name "Dollar" stands representative for a currency whose supply is at the discretion of a monetary institution i.e. a central bank or a smart contract that can react spontaneously to specific market situation.[6] Bitcoin and Dollars compete for usage in trade for chips packages.

Buyers and Sellers To match the experiment, unlike in SSBE and SU, we consider a discrete and finite number of agents in the economy. In the economy, there are two equally sized, infinitely-lived agent groups of six green and six red agents. Both agent types enjoy utility $u(c_{t,j})$ from chips package consumption $c_{t,j} \geq 0$. The utiltiy function is positive, strictly increasing, concave and twice differentiable with $u(0) = 0$. Agents have no utility over money. To create a role for money as a medium of exchange, following SSBE, we assume that the agent groups alternate in consuming and producing the consumption good across time periods, see Figure 1. In even periods, every red agent is exogenously endowed with a constant quantity $y_i = y_{it} = 5$ of packages to sell against either Bitcoin or Dollars to the green agents who are buyers in that period, and thus can consume. In odd periods, the roles revert, and green agents are each endowed with 5 packages to sell to the red agents. With six sellers in the economy, the total chips package supply at any time t equals $Y_t = 30$. In the benchmark case without transaction costs, every package contains 100 chips. Chips are only sold by package which later facilitates the implementation of transaction costs, see below. When later introducing transaction costs, the content of a package can be reduced but the package endowment per seller, and the total package supply in the economy remains the same. Transaction costs in our model, thus, incur in the form of frictions, reducing consumption whereas in the model of SU, costs are added as a tax on the purchase price of a package. We follow SSBE and SU in assuming that either agent groups does not enjoy consuming chips in periods in

[5] Note, the Bitcoin protocol can be thought of as a constrained central bank since it prescribes the increase in the Bitcoin quantity across time, until 21mn Bitcoins are mined. However, unlike for the Dollar, the total Bitcoin quantity cannot be changed discretionary in a way that deviates from the protocol. We abstract from "lost" Bitcoins.

[6] Think, for instance, of the Terra-Luna swap contract that allowed swapping Terra for Luna and vice versa by mining or burning Luna at a rate that did depend on the current Luna price.

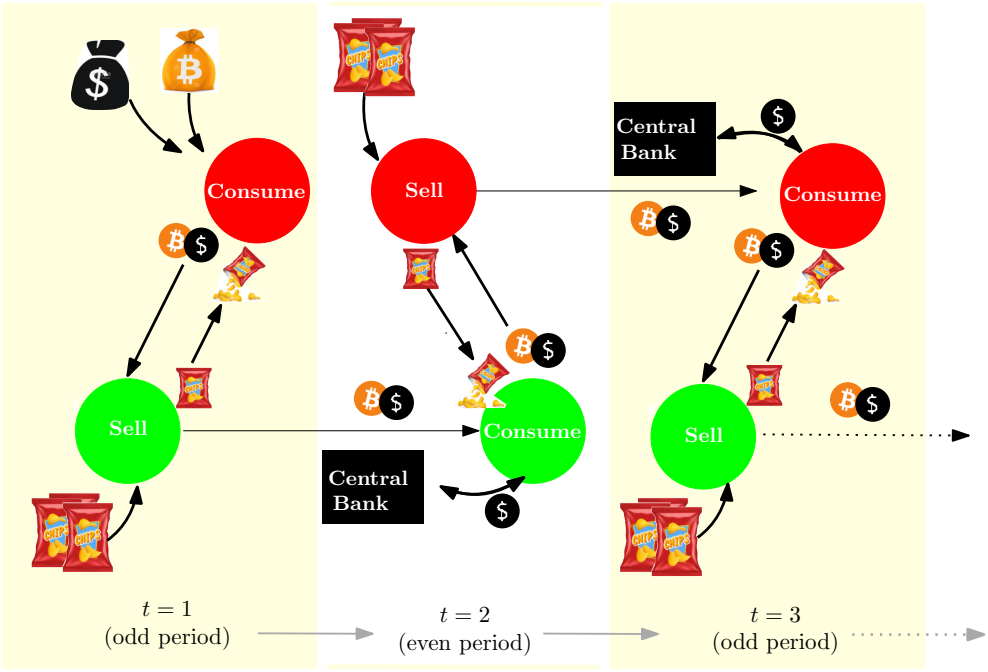


Figure 1: Schematic representation of the structure of the SU model
Notes: Two types of agents, the *red* and the *green* agents, alternate in the role of sellers and buyers of the goods, referred to as chip packages in the experiment.

which they are sellers (cannot consume in the lab when they are a seller). Because goods are perishable the sellers, therefore, do not hold pack goods from the market, and instead have an incentive to sell all of their package endowment to the buyers against Dollars or Bitcoins. By selling goods, the sellers raise funds for financing their goods purchases in the next period when they turn into buyers. The alternating roles of green and red agents as buyers and sellers prevent a double coincidence of wants and induces a motive for trade between the two agent types using money. There exist important search-based micro-foundations for using money in trade, however, our set-up requires less structure which is appealing in the lab where subjects have constrained capacity.

In $t = 1$, the buyers in the economy (red agents) are each endowed with $b_1 = 100$ Bitcoin and $d_1 = 100$ Dollars, implying $B = 600$ and $D_1 = 600$. For $t > 1$, the money balances b_t, d_t evolve according to the trades by the agents, see below. In the benchmark economy, both currencies are perfect substitutes, and are equally accepted for goods purchases from sellers. There exists no Bitcoin central bank. Since we abstract from mining, and "lost" Bitcoins, the Bitcoin supply is constant at level $B \equiv B_t$, both in the model and the experiment.

Denote by D_t the Dollar supply in $t \geq 0$ in the economy. As in (Schilling and Uhlig, 2019b), there exists a Dollar central bank that may want to implement an inflation target by adjusting the Dollar supply D_t in the economy by a multiplier $m > 1$. In the benchmark case, monetary policy by the central bank is muted, $m = 1$, but in a monetary policy treatment, the central bank prints Dollars at zero costs to increase the subjects' Dollar balances proportionally via helicopter drops, $D_t = mD_{t-1} > D_{t-1}$. In the lab, we set $m \in \{1, 1.3\}$ depending on the treatment.

All red and green agents maximize expected discounted life time utility subject to the constraint that all agents become buyers, and hence consume, only every other period,

$$\underbrace{U_g = \sum_{t=0}^{\infty} \beta^{2t} u(c_{2t})}_{\substack{\text{green agents are buyers} \\ \text{and consume in even periods}}} \quad , \quad \underbrace{U_r = \sum_{t=0}^{\infty} \beta^{2t+1} u(c_{2t+1})}_{\substack{\text{red agents are buyers} \\ \text{and consume in odd periods}}} \qquad \beta \in (0,1). \tag{1}$$

Money balances do not enter the utility function.

Trade and market-segmentation In each period, the sellers preallocate their packages to the centralized Dollar- and Bitcoin denominated markets. Let $x_{ti} \geq$ seller i's packages sold in the Bitcoin market and $z_{ti} \geq 0$ the packages sold in the Dollar market. Let $\ell^s_{t,i} \geq 0$ seller i's unsold packages. Sellers face the allocation feasibility constraint

$$y = y_{t,i} = 5 \geq x^s_{t,i} + z^s_{t,i}. \tag{2}$$

Any allocation is possible, meaning a seller can sell all, some or no packages against Dollars and Bitcoin, and there is no segmenation from the sellers' perspective. Only after the sellers' allocation, markets open for trade to the buyers. Thus, unlike in SU and SSBE where at any period, every consumption good can be sold either for Bitcoins or Dollars, here the sellers predetermine the number of packages $Y^B_t = \sum_i x_{ti}$ for sale in the Bitcoin versus $Y^D_t = z_{ti}$ the Dollar market, implying a "semi-segmentation" of the two package markets, $Y \geq Y^B_t + Y^D_t$. Because trade only opens after the sellers have made their allocation choice, the Bitcoin and the Dollar denominated package markets are segmented from the buyers' perspective. Sellers cannot reallocate their packages once trade has opened, and there is no direct currency exchange. Therefore, the sellers are careful as to which market they allocate their packages to. Sellers knows that they will be buyers in the next period, and allocates their packages to the Bitcoin- and Dollar-denominated markets in a way that they are indifferent with regard to receiving either currency. In that regard, despite the semi-segmentation, the Bitcoin and the Dollar denominated package markets are interconnected through the sellers', i.e. next period's buyers' strategies.

Clearing requires

$$Y \equiv Y_t = 30 = Y^B_t + Y^D_t + L_t \tag{3}$$

where L_t are packages that are not offered or unsold in either market, and perish. Every package that is not sold in the Bitcoin package market is either sold for Dollars, or not sold at all. In equilibrium, we should observe $\ell^s_t = 0$, L_t but in the lab, outcomes can differ.

Denote by P_t the market clearing price of a chips package in the Dollar-demoninated goods market, and let $\hat{P}_t$ the market clearing price of a package in the goods market. Let Q_t denote the implicit price of one Bitcoin in terms of Dollars, $\hat{P}_t = P_t/Q_t$, i.e. the Bitcoin exchange rate in Dollars.

Let $d_{t,i}$ denote agent i's individual Dollar balance at the beginning of t, and let $b_{t,i}$ denote her Bitcoin balance both *before* trade occurs in t. A buyers' consumption can be decomposed as Dollar- and Bitcoin financed consumption,

$$c_{t,i} = q^D_{t,i} + q^B_{t,i} \tag{4}$$

where $q^D_{t,i}$ is buyer i's number of packages bought using Dollars, whereas $q^B_{t,i}$ is buyer i's number of packages bought using Bitcoin. A buyer faces a Dollar and a Bitcoin budget constraint

$$P_t q^D_{t,i} \leq d_t, \qquad \hat{P}_t q^B_{t,i} \leq b_t \tag{5}$$

Unlike in SSBE and SU, the agents cannot purchase or consume partial packages to capture the case in the lab. Therefore, q^D_t and q^B_t are always positive integers. The buyers' money balances reduce by the quantity of Dollars, repectively Bitcoins spent. In the next period when she is a seller, her Dollar balance equals

$$d_{t+1,i} = m\,(d_{t,i} - q^D_{t,i} P_t) \tag{6}$$

$$b_{t+1,i} = b_{t,i} - q^B_{t,i} \hat{P}_t. \tag{7}$$

where $m \in \{1, 1.3\}$ is the central bank's money multiplier, depending on the treatment. Here, $d_{t+1,i} \geq$ denote the buyers' Dollar savings, and $b_{t+1,i} \geq 0$ the Bitcoin savings.

The time t-seller's balances are augmented by the sales revenue, and she enters the next time period $t+1$, when she is a buyer, with balances

$$d_{t+1,i} = m\,(d_{t,i} + z^s_{t,i} P_t) \tag{8}$$

$$b_{t+1,i} = b_{t,i} + x^s_{t,i} \hat{P}_t \tag{9}$$

Note that the central bank transfers are proportional to the Dollar balances of buyers and sellers. The central bank multiplies the balances of all agents by factor m at the end of each period t. Therefore, the central bank transfers can be asymmetric agross agents, and may give rise to Dollar hoarding. The multiplier m reflects the central bank's inflation target. Define the Dollar inflation as $\Pi_t = \frac{P_t}{P_{t-1}}$.

Individual money balances need to sum up to the total supply, i.e. there is no currency lost in the economy,

$$B_t = \sum_{i \in I_g \cup I_r} b^i_t, \qquad D_t = \sum_{i \in I_g \cup I_r} d^i_t \tag{10}$$

where I_g denotes the group of gree, and I_r the group of red agents.

Market clearing At time t, the Dollar- and Bitcoin denominated package markets must clear. Because the sellers predetermine the package allocation to markets, we have two market clearing constraints. The total packages sold in either market must equal the total number of packages consumed in that market

$$\begin{cases} Y^B_t & = \sum_{i=1}^6 x_{ti} = \sum_{i=1}^6 q^B_{t,i} \quad \text{(Bitcoin market clearing)} \\ Y^D_t & = \sum_{i=1}^6 z_{ti} = \sum_{i=1}^6 q^D_{t,i} \quad \text{(Dollar market clearing)} \\ Y & \geq Y^B_t + Y^D_t \end{cases} \tag{11}$$

where Y^D_t is the Dollar trade volume, and Y^B_t the Bitcoin trade volume. The total output must equal consumed packages plus unsold or lost packages $Y = 30 = \sum_{i=1}^6 y^s_i = \sum_{i=1}^6 c^s_{t,i} + \sum_{i=1}^6 \ell_{t,i} = \sum_{i=1}^6 (q^B_{t,i} + q^D_{t,i}) + \sum_{i=1}^6 \ell_{t,i}$..

We define the *Dollar trade share*

$$k^C_t \equiv \frac{\sum_i^6 z_{ti}}{Y} \in [0,1] \tag{12}$$

as the share of output sold against Dollars. The Dollar trade volume is governed by the sellers' allocation decisions of packages to the Dollar versus Bitcoin market. Note, that the seller's decisions are substantially influenced by their anticipations of being a buyer in the next period.

Velocity and Quantity theory of money The velocity of money equals the average number of times money changes hands per period. See that the Bitcoin velocity is given as

$$V^B_t = \frac{\hat{P}_t \sum_i^6 q^B_{ti}}{B} \tag{13}$$

and the Dollar velocity as

$$V^D_t = \frac{P_t \sum_i^6 q^D_{ti}}{D_t} \tag{14}$$

since $\hat{P}_t \sum_i q^B_{ti}$ respectively $P_t \sum_i q^D_{ti}$ equal the total number of Bitcoins respectively Dollars spent in t.

Note, by our setup, in every period every Bitcoin or Dollar is spent utmost once. Therefore, the Bitcoin and the Dollar velocity, V_t^B and V_t^D, are each smaller or equal to one, $V_t^B, V_t^D \in [0,1]$. Following Friedman's quantity theory of money and using the market segmentation described above, at any t, the total package output sold in either market must equal the real value of Dollars, respectively Bitcoins spent in that market,

$$Y_t^D = \frac{D_t V_t^D}{P_t} \tag{15}$$

$$Y_t^B = \frac{B_t V_t^B}{\hat{P}_t} = \frac{B_t V_t^B}{P_t} Q_t. \tag{16}$$

Here, $D_t V_t^D$ denotes all Dollars that are exchanged for packages in the Dollar-denominated package market at time t, whereas $B_t V_t^B$ denotes all Bitcoins that are exchanged for packages in the Bitcoin-denominated package market. Currency savings reduce spending, and thus, the velocity of money,

$$V_t^B = \frac{\sum_i^6 \hat{P}_t q_{ti}^B}{B} = \frac{\sum_i^6 b_{ti} - b_{t+1,i}}{B} \tag{17}$$

$$V_t^D = \frac{\sum_i^6 P_t q_{ti}^D}{D} = \frac{\sum_i^6 d_{ti} - d_{t+1,i}/m}{B} \tag{18}$$

2.1 Transaction costs

There is one crucial difference between the transaction cost setting here and in the SU model: in SU, the agents can exchange Bitcoins for Dollars and vice versa whereas we abstract from this possibility. However, in our model, sellers can reallocate packages to the Bitcoin market in anticipation of the buyers unwillingness to buy many packages using Dollars. This rellocation has equal pricing impact via scarcity effects and market clearing as a direct currency exchange would have.

The experiment features treatments with and without transaction costs. Like in the transaction cost model by Schilling and Uhlig (2019b), we apply currency-specific transaction costs. However, unlike in Schilling and Uhlig (2019b), in our setting transaction costs can be quantity-dependent, and are not monetary in the form of taxes but apply in the form of frictions, i.e. "lost consumption.[7]"

In our treatments without transaction costs, a buyer receives and consumes the full content of 100 chips per purchased package, regardless of the currency used for the purchase. In treatments with transaction costs, the subjects consume less than the full content of 100 chips per purchased package. Per round t, a buyer i purchases a total quantity $q_{t,i}^D$ of packages using Dollars, and a quantity $q_{t,i}^B$ using Bitcoins. For packages purchased with Bitcoin, a flat fee of 25% applies so that per package bought with Bitcoins at price $\hat{P}_t$, a buyer consumes only 75%, or 75 chips. One can interprete $\hat{P}_t/0.75$ as the price of a full package purchased with Bitcoin. For packages purchased with Dollars, a quantity-dependent fee applies which increases the more packages were bought using Dollars. Let $1 - r(q_t^D) \in [0,1]$ the average Dollar fee that applies when purchasing q_t^D packages with Dollars in round t.[8] That is, after the Dollar friction is applied, a consumer consumes only $r(q_t^D)$% of the total q_t^D packages purchased with Dollars, each at price P_t. At every new round t, the Dollar costs are reset. One can interprete $P_t / r(q_t^D)$ as the price of a full package purchased with Dollars, if overall q_t^D packages were bought. In theory, agents can purchase arbitrary fractions of a package. Let $\gamma(q_t^D)$ a strictly decreasing, continuous function, describing

[7] In the SU model, the transaction costs apply monetary as a tax, and are redistributed to the sellers of that period.

[8] We need to apply an average here, since the first out of q_t^D packages is bought at a cost of $1 - r_1(1)$%, the second package is bought at a higher cost of $1 - r_2(2)$%, etc.

the marginal after-cost consumption of the q_t^D'th package. For such a continuous function, total Dollar-financed consumption when an agent purchases $q_t^D \in \mathbb{R}_+$ packages using Dollars equals $\int_0^{q_t^D} \gamma(q_t^D) q_t^D$. We can then calculate the average marginal consumption (after costs) $r(q_t^D)$ as

$$r(q_t^D) = \frac{\int_0^{q_t^D} \gamma(k)\, k\, dk}{q_t^D} \tag{19}$$

The marginal change in Dollar-financed after-cost consumption is given as

$$R(q_t^D) \equiv \frac{\partial}{\partial q_t^D}\left(\int_0^{q_t^D} \gamma(k)\, k\, dk\right) = \gamma(q_t^D) q_t^D \tag{20}$$

We define the cut-off quantity $q_t^{D,*}$, as the "critical quantity," i.e. the number of packages at which buyers should optimally switch from making purchases with Dollars to Bitcoin, if prices were equal $P_t = \hat{P}_t$, because the Dollar transaction fee has become too high.

Lab implementation In the lab, however, only full (integer) packages are traded. Table 2.1 gives an overview of the after-cost consumption, $\gamma(q_t^D)$, per additionally bought package used in the lab. Because only full packages are traded in the lab,$\gamma(q_t^D)$ takes the form of a step function. We adjust the Gauss formula[9], to derive a formula for the average marginal consumption,

$$r(q_t^D) = \frac{10 \times 11 - (10 - q_t^D)(10 + 1 - q_t^D)}{2 \times 10 \times q_t^D} = \frac{21 - q_t^D}{20}, \qquad q_t^D \leq 10 \tag{21}$$

We further adjust the marginal change in Dollar-financed consumption to

$$R(q_t^D) \equiv \frac{\partial}{\partial q_t^D}\left(r(q_t^D) q_t^D\right) = \frac{\partial r}{\partial q_t^D} q_t^D + r(q_t^D) = \frac{21 - 2q_t^D}{20} = r(2q_t^D) \tag{22}$$

Table 2.1 gives an overview of the marginal consumption per package depending on the currency used for purchases.

Packages (q_D respect. q_B)	1st	2nd	3rd	4rd	..	10th	11th	12th	⋯	19th and more
Package content after cost, $\gamma(q_t^D) \times 100$ (purchase in dollar)	100	90	80	70	...	10	9	8	⋯	1
Chip content (purchase in bitcoin)	75	75	75	75	...	75	75	75	⋯	75

Table 1: Transaction costs per currency and trade volume. The chips content falls the more packages are purchased using Dollars. The chips content for Bitcoin-purchased packages remains at 75 no matter how many packages are bought using Bitcoin. When a buyer buys more than 3 packages using Dollars, the content falls below 70 chips, i.e. the Dollar transaction costs are higher when using Dollars rather than Bitcoin.

Package (q_D / q_B)	1st	2nd	3rd	4rd	5th ..
$r(q_t^D)$	1	0.95	0.9	0.85	0.8 ..
$R(q_t^D)$	0.95	0.85	0.75	0.65	0.55 ..
Bitcoin $r(q_t^B), R(q_t^B)$	0.75	0.75	0.75	0.75	0.75 ..

Table 2: Marginal consumption after transaction costs per package purchased using Dollars and Bitcoins.

To give an intuition for the Dollar transaction cost, one can think of a loss of privacy. The more purchses a buyer makes using Dollars, the more information is revealed through his purchase history, for instance via online retail payments or bank algorithm tracking, which indirectly reduces his utility from

[9]The sum of the numbers from $1, \ldots, n$ equals $n(n + 1/2)$.

consumption, here modeled by a reduction in the chips content of a package. The flat fee for Bitcoin reflects the transaction fee paid to miners that is proportional to the purchase volume. Recall, that in the lab we call the currencies A (for Dollars) and B (for Bitcoin). Therefore, as long as no monetary policy is implemented by the Dollar central bank on top of transaction costs, "Bitcoin (currency B)" and Dollars (currency A)" are just labels both in the theory and in the lab.[10] One can simply flip labels, and interprete our setting as one where Bitcoin purchases have increasing costs, and Dollar purchases require flat fees. However, we believe that attributing the increasing fee to the Dollar is more reasonable since Bitcoin payments are semi-anonymous.[11]

The market clearing package price in Dollars, P_t, cannot explicitly vary with the transaction cost because a buyer that wants to spend Dollars cannot choose between a low transaction cost or a high transaction cost package, and the seller of that package could not possibly offer different prices depending on the package's chips content. The package price is however indirectly affected by the cost: The Dollar transaction cost $1-r(q_t^D)$ is specific to each buyer, depending on how many packages he/she has already purchased using Dollars in that round. That is, the same package that is offered for sale in the market may differ with regard to its content depending on the identity of the buyer. Because buyers know that the package content goes down the more packages they buy using Dollars, the transaction costs affect a buyers' willingness to use Dollars as a medium of exchange for package purchases, and thus, in the previous round where current buyers are sellers, affects their package allocation to the Dollar versus the Bitcoin market, i.e. affects supply in the segmented markets with implications for prices.

Market clearing When incorporating transaction costs into the economy, the market clearing conditions slightly change due to the frictions.

$$Y = \sum_i c_{t,i} + \sum_i \ell_{t,i} + \sum_i TraCo_{t,i} \tag{23}$$

where $TraCo_{t,i}$ are the transaction costs incurred by agent i. The total package supply must add up to consumed chips, unsold chips packages or chips packages that are lost because the buyers incurred transaction costs.

Model and treatment summary

Table 3: 4 Models/Treatments

Model/Treatment	No transaction costs	Transaction cost (TraCo)
No monetary policy	noInfl, noCost (Benchmark)	noInfl, costs
Monetary policy (MP)	infl, noCost	infl, costs

As we proceed, we address the four different treatments as $m \in \{1, 1.3\}$ and $TraCo \in \{(1,1),((1-r(q_t^D)),0.25)\}$ where the parameters $m = 1$ and $TraCo = (1,1)$ denote the benchmark model and treatment noInfl, noCost.

Definition 2.1 (Equilibrium) *Fix constant output $Y = 30$, a utility function $u(c)$ with $u(0) = 0$, and a discount factor β. Let $m \in \{1, 1.3\}$ the central bank's monetary policy, and let $TraCo \in \{(1,1),((1-r(q_t^D)),0.25)\}$*

[10] With monetary policy, the currency that is governed by a central bank with discretionary Dollar transfers cannot be interpreted as Bitcoin since Bitcoin does not allow money supply deviations from its protocol.

[11] Bitcoin payments can be observed for public addresses but the identity behind the address is generically not known to the Bitcoin network whereas banks and payment providers such as VISA and Paypal know the customer's identity behind account numbers.

the transaction costs imposed in the economy. In either treatment an equilibrium of the trade game between red and green agents consists of
(i) Dollar and Bitcoin price sequences $\{P_t\}_{t\geq 0}$ *and* $\{\hat{P}_t\}_{t\geq 0}$*, implying an exchange rate* $\{Q_t\}_{t\geq 0}$*,* $Q_t = \frac{P_t}{\hat{P}_t}$
(ii) package allocation decisions by sellers to the Dollar market $\{z_t\}_{t\geq 0}$ *and the Bitcoin market* $\{x_t\}_{t\geq 0}$
(iii) consumption-savings decisions by buyers in the Dollar market $\{q_t^D, d_{t+1}\}_{t\geq 0}$ *and the Bitcoin market* $\{q_t^B, b_{t+1}\}_{t\geq 0}$ *such that*

1. *the seller's allocation decisions of packages to the Dollar and the Bitcoin market are optimal given prices subject to feasibility, possible transaction costs, and the Dollar central bank's monetary policy*
2. *the buyers' consumption-savings decisions are optimal given prices subject to both budget constraints, transaction costs and monetary policy*
3. *prices clear package markets* $\sum_i^6 y_{ti} = \sum_i^6 c_{ti} + \sum_i^6 \ell_{ti}$,

$$\sum_i^6 x_{ti} = \sum_i^6 q_{ti}^B, \qquad \sum_i^6 z_{ti} = \sum_i^6 q_{ti}^D$$

3 Model analysis, predictions and hypotheses

In this section, we state the equilibrium conditions of the four different model figurations, and our theoretical predictions. The derivations of the equilibrium conditions can be found in the appendix, section A.1.

Lemma 3.1 *In every treatment* $m \in \{1, 1.3\}$ *the central bank's monetary policy, and let* $TraCo \in \{(1,1),((1-r(q_t^D)),0.25)\}$*, and every treatment-dependent equilibrium* $\{((q_t^{D,*}, d_{t+1}),(q_t^{B,*}, b_{t+1})),(P_t^*, \hat{P}_t^*, Q_t^*),(x_t^*, z_t^*)\}_{t\geq 0}$*, the sellers offer all packages in the market for sales,* $\ell_{ti} = 0$.

Proof: For buyers, the only way to consume is to employ currency for purchasing packages. Therefore, at least one market price P_t or $\hat{P}_t$ is strictly positive. Further, if there was trade in the previous period, then there exists at least one buyer in the following period that holds Dollar, and one agent (possibly the same) that holds Bitcoins (there is at least on buyer in each market with money to pay for goods). Thus, if the sellers offer a package in either market for sale rather than having it decay, because each buyer infers strictly positive utility from one additional package, and the seller infers zero utility from having the package decay, there are gains from trade, and a price inbetween can be found at which both the seller and the buyer are willing to trade.

Hypothesis 3.1 (Market efficiency) *1. In all treatments, all sellers in the lab should optimally sell all of their packages in each period t*

3.1 Benchmark: Equilibrium and Hypothesis

In the benchmark case, there is neither Dollar monetary policy nor transaction costs. Both currencies are perfect substitutes which is why the setting is identical to the perfect foresight model analyzed in Kareken and Wallace (1981) with the intricate difference that here markets are semisegmented because sellers predetermine the allocation of goods to the Bitcoin and the Dollar market. We obtain the following equilibrium conditions

Proposition 3.1 (Equilibrium conditions: Benchmark) *Consider an economy with two competing currencies absent monetary policy and transaction costs. When holding output* $Y = Y_t$*, the Bitcoin supply* B *and the Dollar supply* $D = D_t$ *constant across time, the following equilibrium conditions must hold,*

1. *Inflation/exchange rates (sellers' indifference): Sellers are indifferent w.r.t. allocating packages to the Dollar versus Bitcoin market if the Dollar inflation equals the Bitcoin inflation (Kareken-Wallace)*

$$\frac{\hat{P}_{t+1}}{\hat{P}_t} = \frac{P_{t+1}}{P_t} \tag{24}$$

implying that the Bitcoin price in Dollars (Bitcoin exchange rate) must be constant across time,

$$Q_{t+1} = Q_t = Q_1. \tag{25}$$

2. *Pricing (buyers' consumption-savings): The buyers spend all Dollars on goods if*

$$\beta^2 \frac{1}{P_{t+2}} u'(c_{t+2}) \leq \frac{1}{P_t} u'(c_t) \tag{26}$$

and spend all Bitcoins if

$$\beta^2 \frac{1}{\hat{P}_{t+2}} u'(c_{t+2}) \leq \frac{1}{\hat{P}_t} u'(c_t) \tag{27}$$

In case of equality, the buyers are indifferent with regard to saving or rather consuming an additional package. Indifference in a symmetric equilibrium ($c_t = y_t = 5 = y_{t+2} = c_{t+2}$) yields the Dollar pricing equation

$$\frac{P_{t+2}}{P_t} = \beta^2 \frac{u'(c_{t+2})}{u'(c_t)} = \beta^2. \tag{28}$$

and the Bitcoin pricing equation

$$\frac{\hat{P}_{t+2}}{\hat{P}_t} = \beta^2 \frac{u'(c_{t+2})}{u'(c_t)} = \beta^2 \tag{29}$$

3. *Clearing of both goods markets requires*

$$\begin{cases} Y & = \sum_{i=1}^6 y_{ti} = Y_t^B + Y_t^D = \sum_{i=1}^6 c_{ti} \\ Y_t^B & = \sum_{i=1}^6 x_{ti} = \sum_{i=1}^6 q_{ti}^B = \frac{BV_t^B}{\hat{P}_t} \\ Y_t^D = Y - Y_t^B & = \sum_{i=1}^6 z_{ti} = \sum_{i=1}^6 q_{ti}^D = \frac{DV_t^D}{P_t} \end{cases} \tag{30}$$

and the Dollar trade share equals

$$k_t^C = \frac{\sum_{i=1}^6 q_{ti}^D}{Y} \tag{31}$$

where the Dollar velocity equals the share of Dollars spent in each period, $V_t^D = \frac{\sum_{i=1}^6 q_{ti}^D P_t}{D}$, and the Bitcoin velocity equals the share of Bitcoins spent per period, $V_t^B = \frac{\sum_{i=1}^6 q_{ti}^B \hat{P}_t}{B}$.

Solving for equilibrium The equilibrium equations require the follwing price implications

$$\hat{P}_{t+1} = P_{t+1} \frac{\hat{P}_t}{P_t} = P_{t+1} \frac{\hat{P}_1}{P_1} \tag{32}$$

Further, via backward induction, a symmetric equilibrium requires

$$\hat{P}_{t+2} = \beta^2 \hat{P}_t \leq \hat{P}_t, \qquad P_{t+2} = \beta^2 P_t \leq P_t \tag{33}$$

that is, prices should be weakly decreasing due to the discount factor. Further, Dollar prices evolve according to

$$P_{2t} = \beta^{2t-2} P_2, \quad P_{2t+1} = \beta^{2t} P_1 \tag{34}$$

likewise, Bitcoin prices follow the law of motion

$$\hat{P}_{2t} = \beta^{2t-2}\hat{P}_2, \quad \hat{P}_{2t+1} = \beta^{2t}\hat{P}_1 \tag{35}$$

In short, if the agents save some Bitcoins and Dollars across periods, the prices should be weakly declining, and can, in particular, not increase.

Hypothesis 3.2 (Hypotheses Benchmark economy)

1. *The Dollar inflation should equal the Bitcoin inflation.*
2. *The exchange rate is constant across time*
3. *Dollar and Bitcoin goods prices are weakly decreasing across time*
4. *With $u(0) = 0$ and $\beta < 1$, agents should spend all Dollars and Bitcoins per period*

In line with Kareken-Wallace, the initial goods prices P_1 and $\hat{P}_1$, and thus the initial exchange rate Q_1 are undetermined, but for all following periods, the exchange rate is pinned down. Recall that in the benchmark, both currencies are perfect substitutes. Therefore, any initial package allocation by sellers to markets, and a consecutive exchange rate is reasonable.

3.2 Monetary policy: Equilibrium and Hypothesis

Proposition 3.2 (Equilibrium conditions: Monetary Policy (no Transaction costs)) *Consider an economy with two competing currencies absent transaction costs. We hold output $Y \equiv Y_t$, and the Bitcoin supply B constant across time but we increase the Dollar supply by factor m every period, $D_t = mD_{t-1}$, $m > 1$, by multiplying each of the agents' Dollar balances per time t. The following equilibrium conditions must hold,*

1. *Inflation/exchange rates (sellers' indifference): The inflation on Dollars must equal m-times the inflation on Bitcoin at any point in time,*

$$\frac{P_{t+1}}{P_t} = m\,\frac{\hat{P}_{t+1}}{\hat{P}_t} \tag{36}$$

or equivalently, the Bitcoin price in Dollars (Bitcoin exchange rate) grows at rate m across time

$$Q_{t+1} = m\,Q_t \tag{37}$$

2. *Pricing (buyers' consumption-savings): The buyers spend all Dollars on goods if*

$$\beta^2 m^2 \frac{1}{P_{t+2}} u'(c_{t+2}) \leq \frac{1}{P_t} u'(c_t) \tag{38}$$

and spend all Bitcoins if

$$\beta^2 \frac{1}{\hat{P}_{t+2}} u'(c_{t+2}) \leq \frac{1}{\hat{P}_t} u'(c_t) \tag{39}$$

In case of equality, the buyers are indifferent with regard to saving and consuming. Indifference in a symmetric equilibrium ($c_t = y_t = 5 = y_{t+2} = c_{t+2}$) yields

$$\frac{P_{t+2}}{P_t} = \beta^2 m^2\,\frac{u'(c_{t+2})}{u'(c_t)} = \beta^2 m^2. \tag{40}$$

$$\frac{\hat{P}_{t+2}}{\hat{P}_t} = \beta^2 \frac{u'(c_{t+2})}{u'(c_t)} = \beta^2 \tag{41}$$

3. *Clearing of both goods markets requires*

$$\begin{cases} Y & = \sum_{i=1}^{6} y_{ti} = Y_t^B + Y_t^D = \sum_{i=1}^{6} c_{ti} \\ Y_t^B & = \sum_{i=1}^{6} x_{ti} = \sum_{i=1}^{6} q_{ti}^B = \frac{B V_t^B}{\hat{P}_t} \\ Y_t^D = Y - Y_t^B & = \sum_{i=1}^{6} z_{ti} = \sum_{i=1}^{6} q_{ti}^D = \frac{D_t V_t^D}{P_t} = \frac{m D_{t-1} V_t^D}{P_t} \end{cases} \tag{42}$$

Solving for MP equilibrium Given the goods prices in the initial period P_1 and $\hat{P}_1$, the Dollar and the Bitcoin prices for goods are interconnected by the equation

$$\hat{P}_{t+1} = \frac{1}{m} P_{t+1} \frac{\hat{P}_t}{P_t} = \frac{1}{m^t} P_{t+1} \frac{\hat{P}_1}{P_1} \tag{43}$$

The equation says that the Dollar inflation must equal m-times the Bitcoin inflation, where $m > 1$.

Without monetary policy, $m = 1$, sellers prefer Dollars, if the Dollar inflation is below the Bitcoin inflation, $\hat{P}_{t+1} \geq P_{t+1} \frac{\hat{P}_t}{P_t}$, because tomorrow sellers are buyers, and want to sell against the less inflationary currency today. With monetary policy, sellers prefer Dollars, if $\hat{P}_{t+1} \geq \frac{1}{m} P_{t+1} \frac{\hat{P}_t}{P_t}$. That is, if the Dollar price does not grow fast enough relative to m, sellers are no longer indifferent and reallocate packages to the Dollar market since holding Dollars overnight yields a high central bank multiplier m that outweighs Dollar inflation that may be higher than Bitcoin inflation. That is, for $\frac{P_{t+1}}{P_t} \geq \frac{\hat{P}_{t+1}}{\hat{P}_t} \geq \frac{1}{m} \frac{P_{t+1}}{P_t}$, sellers stick to Dollar sales.

Hypothesis 3.3 (Hypotheses: Monetary Policy (no Tra Co)) *Fix $m > 1$.*

1. *The Dollar inflation should equal m-times the Bitcoin inflation.*
2. *The Bitcoin exchange rate, i.e. the price of a Bitcoin denominated in Dollars should grow at the rate m, $Q_{t+1} = mQ_t = m^t Q_1$ for all $t \geq 1$.*
3. *If not all Bitcoins and Dollars are spent in every period (which we observe in the experiment), Bitcoin prices are weakly decreasing across time whereas Dollar prices increase if $\beta m > 1$, and decrease if $\beta m < 1$. If the Dollar price P_{t+2} does not raise fast enough, Dollar savings increase (velocity declines) because buyers rather take advantage of the large multiplier than spend today.*
4. *Sellers reallocate packages to the Dollar market, Y_t^D increases, if the Dollar price does not grow fast enough, i.e. if $\hat{P}_{t+1} \geq \frac{1}{m} P_{t+1} \frac{\hat{P}_t}{P_t}$ holds.*
5. *Market clearing: By the market clearing conditions in the Dollar market, because the Dollar supply increases by factor m overnight, either the Dollar price must increase, or the Dollar savings must go up (Dollar velocity declines), or the sellers allocate packages from the Bitcoin to the Dollar market, or combinations of those three.*

$$Y_{t-1}^D = Y - Y_{t-1}^B = \frac{D_{t-1} V_{t-1}^D}{P_{t-1}}$$

$$Y_t^D = Y - Y_t^B = \frac{D_t V_t^D}{P_t} = \frac{m D_{t-1} V_t^D}{P_t}$$

.

If the sellers reallocate packges to the Dollar market, there are fewer packages in the Bitcoin market, and scarcity jointly with market clearing either requires the Bitcoin package price to increase or the Dollar velocity to decline (more savings) or both, $Y_t^B = \sum_{i=1}^{6} x_{ti} = \sum_{i=1}^{6} q_{ti}^B = \frac{B V_t^B}{\hat{P}_t}$.

Equation (43) says that if the Dollar price P_{t+1} increases, the Bitcoin price adjusts slower, or may even decrease. E.g., if $Pt+1 = P_t n, n < m$, then $\hat{P}_{t+1} = \frac{1}{m} P_{t+1} \frac{\hat{P}_t}{P_t} = \frac{n}{m} P_t \frac{\hat{P}_t}{P_t} = \frac{n}{m} \hat{P}_t < \hat{P}_t$.

Unlike in classic monetary models with only one currency in the economy, an increase in the Dollar supply at constant output does not necessarily imply an increase in the Dollar price level, and thus Dollar inflation. Schilling and Uhlig (2019a) show that, absent transaction costs, an increase in the Dollar supply can cause deflation in the Bitcoin price, instead of inflation in the Dollar. Likewise, the SU model shows that Dollar inflation may shift the critical good (here the critical quantity) at which the buyers switch from using Dollars to Bitcoin for making their purchases.

In the SU model, the structure of the transaction costs additionally pins down the steady-state level of the critical quantity of packages q_D, which determines the share of goods exchanged for in dollars and in bitcoins.

3.3 Transaction costs: Equilibrium and Hypothesis

Proposition 3.3 (Equilibrium: Transaction costs (no Monetary policy)) *Consider an economy with two competing currencies absent monetary policy. We hold output $Y \equiv Y_t$, the Bitcoin supply B, and the Dollar supply D constant across time. There are transaction costs on purchases with either currency, given in table 2.1 and 2.1. The following equilibrium conditions apply*

1. *Inflation/exchange rates (sellers' indifference):*

$$\frac{P_{t+1}}{P_t} = \frac{R(q_t^D)}{0.75} \frac{\hat{P}_{t+1}}{\hat{P}_t}. \tag{44}$$

and thus

$$\hat{P}_{t+1} = \frac{0.75}{R(q_t^D)} P_{t+1} \frac{\hat{P}_t}{P_t} = \frac{0.75^t}{\prod_{k=1}^t R(q_k^D)} P_{t+1} \frac{\hat{P}_1}{P_1}. \tag{45}$$

In a symmetric equilibrium, q_t^D is constant across time, thus $\hat{P}_{t+1} = \frac{0.75}{R(q_t^D)} P_{t+1} \frac{\hat{P}_t}{P_t} = \left(\frac{0.75}{R(q_1^D)}\right)^t P_{t+1} \frac{\hat{P}_1}{P_1}$. Writing this equilibrium condition in terms of the exchange rate, we obtain

$$Q_{t+1} = \frac{R(q_t^D)}{0.75} Q_t = \left(\frac{R(q_1^D)}{0.75}\right)^t Q_1 \tag{46}$$

2. *Pricing (buyers' consumption savings condition): Buyers spend all Dollars if*

$$\beta^2 R(q_{t+2}^D) \frac{1}{P_{t+2}} u'(c_{t+2}) \leq R(q_t^D) \frac{1}{P_t} u'(c_t) \tag{47}$$

and Bitcoins if

$$\beta^2 \frac{1}{\hat{P}_{t+2}} u'(c_{t+2}) \leq \frac{1}{\hat{P}_t} u'(c_t) \tag{48}$$

3. *Savings: If some but not all Dollars and Bitcoins are spent in each period, i.e. if there are savings in either currency, then the consumption Euler equations in a symmetric equilibrium ($c_{t+2} = y = c_t$) become*

$$\frac{\hat{P}_{t+2}}{\hat{P}_t} = \beta^2 \frac{u'(c_{t+2})}{u'(c_t)} = \beta^2. \tag{49}$$

$$\frac{P_{t+2}}{P_t} = \beta^2 \frac{R(q_{t+2}^D)}{R(q_t^D)} \frac{u'(c_{t+2})}{u'(c_t)} = \beta^2 \frac{R(q_{t+2}^D)}{R(q_t^D)} \tag{50}$$

here $\frac{R(q^D_{t+2})}{R(q^D_t)} = 1$ *in a symmetric equilibrium.*

4. *Market clearing of both goods markets requires*

$$\begin{cases} Y & = \sum_{i=1}^{6} y_{ti} = Y^B_t + Y^D_t = \sum_{i=1}^{6} c_{ti} + \sum_{i=1}^{6} TraCo_{ti} \\ Y^B_t & = \sum_{i=1}^{6} x_{ti} = \sum_{i=1}^{6} 0.75\, q^B_{ti} + \underbrace{0.25\, q^B_{ti}}_{\text{transaction costs}} = 0.75\, \frac{B V^B_t}{\hat{P}_t} + \underbrace{0.25\, \frac{B V^B_t}{\hat{P}_t}}_{\text{transaction costs}} \\ Y^D_t = Y - Y^B_t & = \sum_{i=1}^{6} z_{ti} = \sum_{i=1}^{6} r_t(q^D_t)\, q^D_{ti} + \underbrace{(1 - r_t(q^D_t)) q^D_{ti}}_{\text{transaction costs}} = r_t(q^D_t)\, \frac{D V^D_t}{P_t} + \underbrace{(1 - r_t(q^D_t))\, \frac{D V^D_t}{P_t}}_{\text{transaction costs}} \end{cases} \tag{51}$$

See that in equation (49), the Bitcoin transaction cost has cancelled out. By its constancy, the Bitcoin transaction cost has no impact on the buyers' consumption savings decision. In contrast, equation (50) shows that Dollar pricing, and Dollar consumption-savings do depend on the Dollar transaction costs, if the buyer consumes different quantities at t versus $t+1$, and thus incurs different marginal Dollar transaction costs.

The transaction costs reduce the individual and the aggregate consumption. Therefore, in comparison to the benchmark without transaction costs, either the Dollar and Bitcoin prices must be higher or the velocities must be smaller to clear the market.

The share of consumption lost due to transaction costs is endogenous in the currency choice. The sellers' indifference requires that the Dollar inflation times the marginal consumption after Bitcoin transaction costs must equal the Bitcoin inflation times the marginal consumption after Dollar transaction costs. Recall that for the sellers' choice $z_t = q^D_t = 3$, it holds $R(3) = 0.75$, so that the Dollar and the Bitcoin after-fee consumption exactly cancels.

Hypothesis 3.4 (Hypotheses: Transaction costs (no MP))

1. *The sellers allocate packages to the markets to equalize transaction costs,* $R(q^D_t)) = 0.75$*, by choosing* $z_{ti} = q^D_{ti} = 3$*, yielding a Dollar trade share of* $6 \times 3 / Y = 18/30 = 0.6$*, and prices rise such that inflation rates are equal*
2. *Given sellers choose* $z_{ti} = q^D_{ti} = 3$*, the exchange rate is constant*
3. *The Bitcoin price is weakly decreasing across time*
4. *In a symmetric equilibrium, with* $z_{ti} = q^D_{ti} = 3$ *constant, the Dollar price is weakly decreasing.*
5. *With* $u(0) = 0$ *and* $\beta < 1$*, agents should spend all Dollars and Bitcoins per period*

3.4 Transaction costs and Monetary Policy

Proposition 3.4 (Equilibrium: Transaction costs with Monetary policy) *Consider an economy with two competing currencies. We hold output* $Y \equiv Y_t$*, and the Bitcoin supply* B_t *constant, but the Dollar supply increases by factor* m *per period by multiplying all of the agents' Dollar balances,* $D_t = mD_{t-1}$*. We impose transaction costs on purchases with either currency, given in table 2.1 and 2.1. Equilibrium requires that*

1. *Inflation/exchange rates (sellers' indifference):*

$$\frac{P_{t+1}}{P_t} = m\, \frac{R(q^D_t)}{0.75}\, \frac{\hat{P}_{t+1}}{\hat{P}_t}. \tag{52}$$

or

$$\hat{P}_{t+1} = \frac{1}{m}\frac{0.75}{R(q_t^D)}\,P_{t+1}\frac{\hat{P}_t}{P_t} = \left(\frac{1}{m^t}\,\frac{0.75^t}{\prod_{k=1}^{t} R(q_k^D)}\right) P_{t+1}\,\frac{\hat{P}_1}{P_1}. \tag{53}$$

Equivalently, the exchange rate (Bitcoin price in Dollars evolves according to)

$$Q_{t+1} = m\,\frac{R(q_t^D)}{0.75}\,Q_t = m^t\left(\frac{\prod_{k=1}^{t} R(q_k^D)}{0.75^t}\right) Q_1 \tag{54}$$

2. *Consumption-savings (Buyers' indifference): As long as some Dollars and Bitcoins are spent in each period, the following pricing inequalities must hold*

$$\beta^2\, m^2\, R(q_{t+2}^D)\,\frac{1}{P_{t+2}}u'(c_{t+2}) \le R(q_t^D)\,\frac{1}{P_t}u'(c_t) \tag{55}$$

and

$$\beta^2\frac{1}{\hat{P}_{t+2}}u'(c_{t+2}) \le \frac{1}{\hat{P}_t}u'(c_t) \tag{56}$$

Savings: If some but not all Dollars and Bitcoins are spent in each period, indifference requires

$$\frac{\hat{P}_{t+2}}{\hat{P}_t} = \beta^2\frac{u'(c_{t+2})}{u'(c_t)} \tag{57}$$

For Dollars,

$$\frac{P_{t+2}}{P_t} = \beta^2\, m^2\,\frac{R(q_{t+2}^D)}{R(q_t^D)}\,\frac{u'(c_{t+2})}{u'(c_t)} \tag{58}$$

3. *Market clearing of both goods markets requires*

$$\begin{cases} Y & = \sum_{i=1}^{6} y_{ti} = Y_t^B + Y_t^D = \sum_{i=1}^{6} c_{ti} + \sum_{i=1}^{6} TraCo_{ti} \\ Y_t^B & = \sum_{i=1}^{6} x_{ti} = 0.75\,\frac{B\,V_t^B}{\hat{P}_t} + \underbrace{0.25\,\frac{B\,V_t^B}{\hat{P}_t}}_{\text{transaction costs}} \\ Y_t^D = Y - Y_t^B & = r_t(q_t^D)\,\frac{D_t\,V_t^D}{P_t} + \underbrace{(1-r_t(q_t^D))\,\frac{D\,V_t^D}{P_t}}_{\text{transaction costs}} = r_t(q_t^D)\,\frac{mD_{t-1}\,V_t^D}{P_t} + \underbrace{(1-r_t(q_t^D))\,\frac{mD_{t-1}\,V_t^D}{P_t}}_{\text{transaction costs}} \end{cases} \tag{59}$$

Since the marginal Bitcoin transaction cost is constant in the number of packages purchased, it cancels out in equation (57) and does not affect optimal Bitcoin savings and consumptions.

Hypothesis 3.5 (Hypotheses: Transaction costs with MP)

1. *Sellers allocate packages to markets to equalize transaction costs,* $R(q_t^D)) = 0.75$*, by choosing* $z_{ti} = q_{ti}^D = 3$*, yielding a Dollar trade share of* $6 \times 3/Y = 18/30 = 0.6$*, and prices rise such that the Dollar inflation is* m*-times larger than the Bitcoin inflation*

   - *If the sellers' allocation to the Dollar market,* $z_{ti} = q_{ti}^D$*, declines over time, then* $R(q_{t+2}^D)/R(q_t^D) > 1$*, and transactions costs amplify the monetary policy effect on Dollar prices, i.e. Dollar prices increase faster than with monetary policy only.*

   - *If the sellers' allocation to the Dollar market,* $z_{ti} = q_{ti}^D$*, increases over time, then* $R(q_{t+2}^D)/R(q_t^D) < 1$*, and transactions costs dampen the monetary policy effect on Dollar prices, i.e. Dollar prices increase slower than with monetary policy only.*

2. *Given sellers choose $z_{ti} = q^D_{ti} = 3$, the exchange rate grows at rate m*

3. *The Bitcoin price is weakly decreasing across time*

Both kinds of equilibria may be constructed and the theory is agnostic as to which one may prevail. Our experiment may help discriminate between these equilibria by pointing at the ones that emerges in the lab as the ones that may be empirically relevant. Can the Dollar inflation stay constant if the critical good adjusts to changes in the money supply? What are the circumstances that cause a crowding-out of the Dollar (i.e., a decline in the critical good k^c) or a crowding-out of the Bitcoin (i.e., an increase in the critical good k^c)?

Our experiment aims to test these predictions with a focus on equilibrium selection. We address two sets of questions. First, do the experimental market forces achieve an efficient coordination between buyers and sellers on a constant critical quantity? If so, which share of the goods is traded in Bitcoin versus Dollar? Second, how does monetary policy affect currency substitution, i.e. how does the critical good adjust to changes in the money supply? Do CB transfers result in a crowding out of the Bitcoin in the absence of transaction costs and a crowding out of the Dollar in the presence of transaction costs, as the model suggests? In both cases, what is the realized rate of Dollar price inflation? Before discussing the experimental results along this set of questions, we briefly describe the lab implementation.

4 The experimental environment

We design a group experiment with a between-subject design based on the infinite-time horizon frameworks of Schilling and Uhlig (2019a,b); see Fig. 1 for an illustration of its overall structure.

To emulate SU's infinite-horizon, perfect foresight environment with discounting in the lab, our experiment utilizes independent repetitions, or sequences, of the experimental game with a stochastic ending, which is in line with the related literature (Fréchette and Yuksel, 2017). Each round within an experimental sequence represents one time period in the infinite-horizon game. The probability of the experimental sequence to continue after each round is constant at $\beta = 5/6$ and common knowledge among the subjects, proxying for the discount factor of the underlying model. At the end of each trading round, the sequence in our experiment ends with probability 1/6 (where we use the metaphor of a dice roll), to induce impatience, a critical assumption of the SU model; see App. **??**. After a stochastic ending of one experimental sequence, a new sequence among the subjects starts. Accordingly, our subjects played repeated sequences of trades composed of an unknown number of rounds so as to fill a two-hour lab session. For each of the four treatments, introduced below, we recruited 6 independent groups of subjects, where each group represented one economy.

Alternating roles Following SU, in the experiment we model two agent groups, calling them red and green agents, who alternate in their roles as sellers and buyers of the consumption good. To facilitate the experiment, unlike in SU, we model only a single, perishable consumption good "chips packages", as in Schilling and Uhlig (2019a). However, we continue following SU regarding the implementation of transaction costs. While SU denote these currencies as Dollar and Bitcoin, in the experiment we adopt a neutral language, calling the currencies 'Currency A' (for Dollar), and 'Currency B' (for Bitcoin).

For the purpose of the lab implementation, we consider a finite and discrete set of agents. We recruit 12 subjects per experimental economy, of which there are $N_r = 6$ red agents and $N_g = 6$ green agents in every round of the experiment.[12] In the first round of each trade sequence, half of the subjects are

[12] Six market participants have proven to be sufficient to induce competition and hinder collusion, see e.g. Dufwenberg and Gneezy (2000), while keeping the scale of the experiment small enough to collect many independent observations, i.e., $24 = 4 \times 6$

randomly assigned to a seller role, and the other half become buyers. Subjects then alternate in these roles throughout each sequence. For instance, if assigned the role of a buyer in round 1, a subject will be a seller in period 2, then a buyer again in period 3, etc., until the sequence ends and a new random draw is performed to pick the sellers and buyers for the next sequence.

Trade The experiment starts in round $t = 1$ with an initial total money supply of 600 Bitcoins and Dollars, respectively, $B_1 = D_1 = 600$. In $t = 1$, the six buyers start with a symmetric endowment of currency balances, amounting to an equal share of the initial currency supply, so that each buyer receives 100 dollars and 100 bitcoins in $t = 1$, before trade opens.

In each round of a trading sequence, the sellers are endowed with the constant amount of $y_{i,t} = \bar{y} = 5$ perishable chips packages per experimental round, where each package contains 100 chips. The constancy of package endowments is common knowledge among the subjects. Sales occurs per package. The content of 100 chips per package holds for the benchmark experimental design absent transaction costs. When we introduce transaction costs later, the number of chips per package is reduced to mimick frictions.

In each round, the subjects that are currently sellers choose an allocation of their 5 packages between the two currency-denominated goods markets, before trade opens. Any allocation of packages to markets is feasible, including selling all packages in only one market, e.g. only against Dollars or only against Bitcoins. A seller can hold back packages from sales, however packages perish across experimental rounds so that sellers have no motive to hold back packages for themselves. Moreover, we disallow the subjects to consume in periods in which they are sellers, in line with the SU and SSBE models, to generate a motive for trade using money. The sellers have 30 seconds to allocate packages to markets in each round, and then markets open for trade for 90 seconds.

Unlike in the models of Schilling and Uhlig (2019b) and Schilling and Uhlig (2019a), the Dollar- and Bitcoin denominated package markets are semi-segmented in our experiment: On the one hand, the sellers can freely allocate their packages to the Bitcoin- or the Dollar denominated market. On the other hand, once trading starts, the sellers cannot reallocate their packages across markets, and the buyer subjects do not have the possibility to directly exchange Bitcoins for Dollars, or vice versa.[13] This semi-segmentation in the experiment means that the sellers are commited to their markets, and cannot directly react if the trade conditions are much better in the Bitcoin-package market relative to the Dollar package market, e.g. if the overall package supply in the Bitcoin market is currently low such that the package price for Bitcoin is quite high in that particular trading round. Rather, the reaction to current market conditions is delayed by two periods because then the current sellers are sellers again.

In the experiment, we implement trade using two separate, currency-specific auction houses, each operating a continuous double auction (CDA) mechanism; see the trading interface of a buyer in Figure 2 for illustration. In every trading round and in each market, the seller-subjects submit asks whereas the buyers-subjects submit bids. Bids and asks consist of a quantity and a price at which the submitting subject is willing to trade. All buyer-subjects are subject to a no-borrowing or no short-selling constraints whereas the seller-subjects can maximally sell the number of packages they allocated to that particular market. Trade between a buyer and a seller occurs, i.e. they are automatically matched, whenever a seller's posted ask price is below or equals a buyer's posted bid price. In the case of multiple possible matches, i.e. when multiple ask prices of sellers are below the bid of a buyer, the buyers are automatically

experimental economies in total.

[13] In contrast, in Schilling and Uhlig (2019b) and Schilling and Uhlig (2019a) the sellers quote both Bitcoin and Dollar prices for each consumption good, so that the full supply of goods is simultaneously for sale against Dollars or Bitcoins.

matched to the best, i.e. lowest ask price. The experiment imposes, that the transaction price equals the seller's ask price and the number of packages exchanged equals the minimum of the number of packages offered by the seller and those desired by the buyer. If the seller has access supply, the seller can be rematched to another buyer after that trade is settled. Note that, because trades are always settled at the best ask price for the buyer, this creates a motive for sellers to delay posting their ask prices to observe the market conditions. The delay of the sellers, on the other hand, creates a motive for the buyers to, vice versa, delay their bids. In the experiment, the sellers observes all the incoming bids on the screen, whereas the buyers observe all the incoming asks. The buyers can submit multiple bids in each market. Those bids may exceed their budget constraints, in each currency. The software takes care, that once a buyer's bid gets accepted, bids that are not within that buyers' budget constraint get deleted. Likewise, the software enforces the sellers' capacity constraints, meaning the seller cannot sell more packages than he has allocated to either market.

Bids and asks may be retracted as long as they have not been accepted by the other party. The participants may submit as many asks and bids as desired during the 90 seconds of trade. For a buyer and sellers, instead of submitting a bid respectively an ask price, (s)he can also use a short-cut provided by the interface: on each market there exists a button to click and accept the best standing trade, i.e. sellers can accept the best (highest) bid, and buyers can accept the best (lowest) ask to instantly trade. This allows them to prevent the automatic matching.

The auction houses can close earlier than 90 seconds if one side of the market becomes exhausted. After the 90 seconds of trade, unspent currency holdings are transferred to the next round while unsold packages perish and disappear. The sellers use their sales income, denominated in Bitcoin and Dollars, to buy packages in the next period when they are a buyer.

In any further period $t > 1$, the trades proceed as described and impact the currency holdings of the trading agents across time. Money balances carry over from round to round until they are reset at the random end of a sequence.

Monetary policy In the lab, we implement changes to the Dollar supply through lump-sum transfers τ_t to the subjects' Dollar balances across rounds. We seek to implement a Dollar inflation target $\bar{\pi} \equiv \frac{P_t}{P_{t-1}} \geq 1$, by letting the quantity of dollars grow by central bank transfers in each trading round. Precisely, we multiply each subjects' dollar balance, buyers and sellers, in the economy by $\bar{\pi} = 1.3$ at the end of each round, which implies strictly positive central bank transfers. Because the transfers are proportional to the existing Dollar balances, the transfers are asymmetric across all subjects, see Jiang et al. (2021) for a discussion on lump-sum versus proportionate transfers.

Since in the real world, there is no Bitcoin central bank to discretionary lower or increase the Bitcoin supply, we leave the quantity of Bitcoin constant throughout each trading sequence.[14] Therefore, the Bitcoin balances of the subjects only change across time via trade in goods whereas Dollar balances change according to trade and Dollar monetary policy.

At the beginning of a new experimental sequence, all money balances are reinitialized to zero for the sellers and 100 for the buyers.

Transaction costs To implement transaction costs for Bitcoin and Dollar denominated purchases in each trading round, we reduce the content of each chips package depending on the demanded quantity per currency at a given price. The reduction in content is currency-specific and depends on how

[14] Implicitly this means, that we abstract from Bitcoin mining across the experiment.

many packages have been purchased with one specific currency in one round. In the next round, the transaction costs restart at zero, and then increase as a buyer makes more purchases with one particular currency in that round. For the k' th package, the transaction cost is denoted by $1-\gamma(k) \in (0,1)$ when buying the k'th package in Dollars and $1-\alpha(k) \in (0,1)$ when purchasing it using Bitcoins. This means, the buyer receives a consumption of $\gamma(k) \times 100 < 100$ chips for the k'th package when purchased in Dollars or $\alpha(k) \times 100 < 100$ chips for the k'th package when purchased in Bitcoin. When selling one unit of a good k, the seller receives the full amount of the price of P dollars (or $\hat{P}$ bitcoins), i.e. the pre transaction cost price. While in our set-up, the transaction costs lower the content of a package, in the SU model, the transaction costs are applied to the price, essentially raising the costs for the same number of consumption goods. Our implementation of transaction costs boils down to the same unit price per chip in the experiment as in the theoretical model while being easier to understand for the subjects.[15]

As a further difference, in the SU model, the costs are paid out to the sellers as lump-sum transfers, whereas in our setting and in the lab we assume that the number of chips lost due to the transaction costs vanish from the economy due to frictions.

The experimental subjects' incentives

We compensate the subjects for their efforts in the following way. Purchased chips (goods) are directly converted into euros paid out at the end of the experiment. Experimental bitcoin and dollar balances, in contrast, are not paid out, and are thus worthless as such, imposing the fiat money property, and avoiding currency hoarding. Since the subjects alternate in their roles, buying chips, and therefore accruing real world payoff is only possible every other period. The monetary incentive for the sellers lies in selling their packages to increase their currency holdings, which allows them to buy packages when they become a buyer in the next round.

To emulate consumption smoothing, we use the following CRRA function to convert any positive number of purchased chips into euros: $\frac{\sqrt{\#chips}}{10}$. At the end of the experiment, we pay out the cumulative (real world) earnings over all rounds of two randomly drawn sequences to the participants.[16]

Experimental Timing To sum up, in each round of a given sequence, the events unfold as follows:

1. In the first round of each sequence ($t = 1$), buyers receive an endowment of 100 dollars and 100 bitcoins. Sellers receive a endowment of 5 goods packages of 100 chips.

   In any further rounds ($t > 1$): Sellers continue being endowed with 5 packages per round, whereas the buyers hold money balances that result from the previous round's sales proceeds when those buyers were sellers. In addition, the buyers' money balances can be altered across rounds by central bank monetary policy whereas the package chips content may fall below 100 in each round, depending on the subjects play the economy with transaction costs or not.

2. Central bank monetary policy is implemented via changes in the Dollar money supply (currency A). The central bank changes the supply by transferring positive quantities of Dollars to the buyer subjects' Dollar wallet: each dollar is multiplied by $\bar{\pi} = 1.3$ per round for both buyers and sellers.

3. Every round, the sellers have 30 seconds to allocate their packages across the two currency-specific auction houses.

[15] The only difference is that in the lab, the transaction costs impact directly the buyers' utility and the equilibrium on the goods market reads as: $y_t = c_t + \text{transaction costs}_t$.

[16] Not paying the entire history of the game prevents wealth effects as participants do not know which sequences will be paid out at the end of the session and selecting two sequences is necessary to ensure reasonable payoff levels.

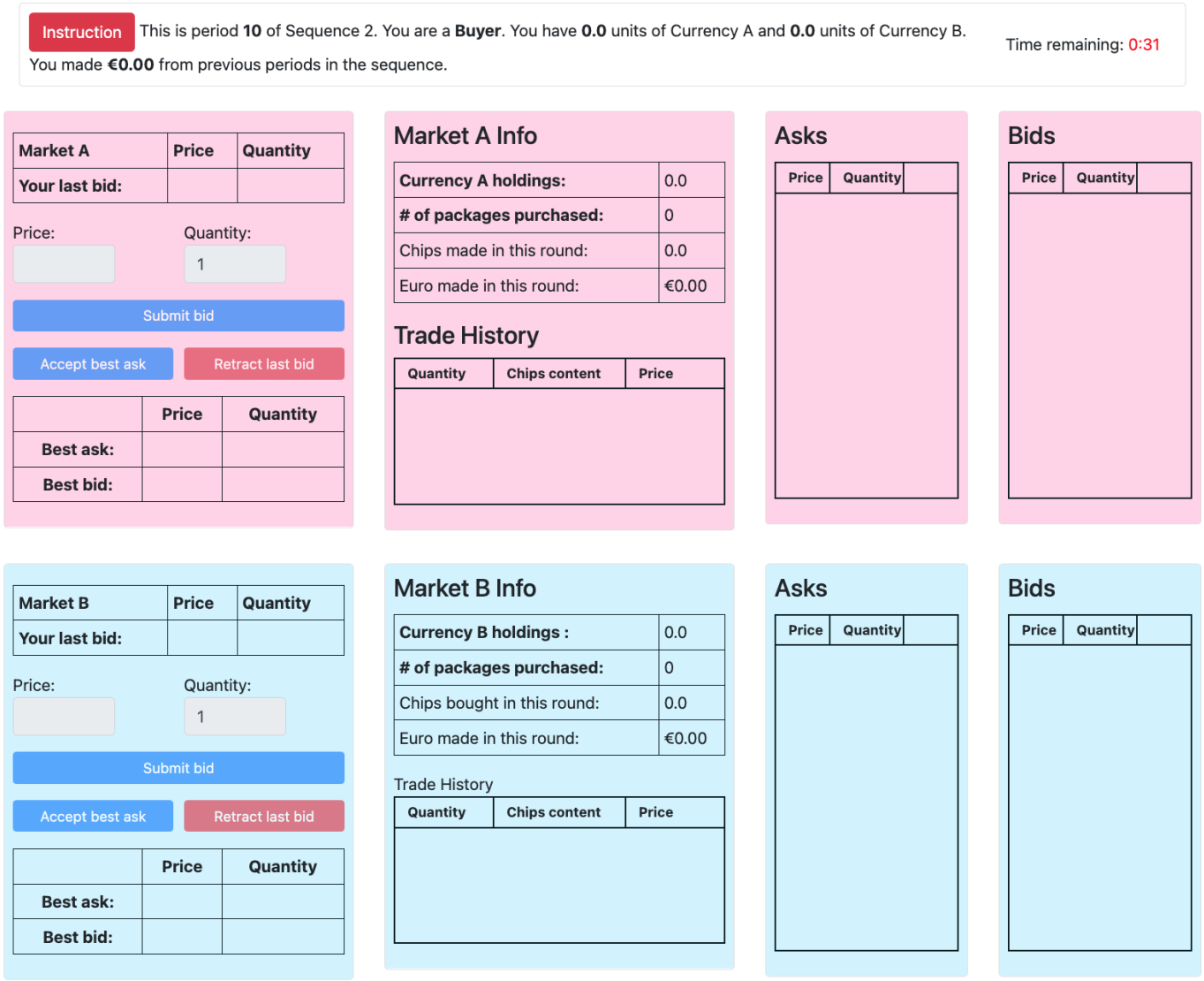


Figure 2: Graphical user interface of the buyer

Notes: The dollar-denominated and bitcoin denominated trading interfaces are, respectively, on the top (market A in red) and on the bottom (market B in blue). Subjects submit their bids (and symmetrically their asks for the sellers) on the left-hand side column. The middle panel provides the details of the subject's trading history on each market so far in the given round, and the right-hand side panel displays all the asks and bids in each market as soon as they posted. The instructions and the guidance of the experimenter during the training periods make this interface clear to the subjects.

4. Subsequently, the two auction houses open for a maximum of 1.5 minutes. The purchased chips instantaneously accumulate towards the buyers' real world earnings while sellers accrue their dollar and bitcoin currency balances by the sales proceeds.

5. Then, the subjects observe whether the sequence continues, with probability $\frac{5}{6}$, or ends with probability $\frac{1}{6}$. If the sequence continues, the roles of buyers and sellers flip, currency balances carry over to the next round at $t+1$, while unsold packages perish and disappear. If the sequence ends, a new one starts and currency balances are reinitialized as in Step 1.

4.1 Treatments

We use a 2-by-2 design where the two treatment variables are the expansion of the dollar supply via central bank monetary policy and transaction costs. The two treatments per monetary policy and trans-

action cost overall yield 4 different scenarios that we test in the lab.

4.1.1 Treatments

First monetary policy treatment: `noInfl`: The first treatment variable is the gross Dollar inflation target, denoted by $\bar{\pi}$.
In a first treatment, identified by `noInfl`, we set the Dollar inflation target to zero across periods, $\bar{\pi} = 1$, which rules out any central bank Dollar transfers to the subjects, $\tau_t = 0$, $\forall t$. The dollar supply, therefore, remains constant per round at $D \equiv D_t$ throughout the trading sequences.

Second monetary policy treatment: `infl`: In the other set of experimental economies, identified by `infl`, we implement a dollar inflation target of $\bar{\pi} = 1.3$. To do so, we let the quantity of dollars grow by central bank transfers to the subjects' Dollar balances in each trading round, multiplying every dollar balance in the economy by $\bar{\pi} = 1.3$ at the end of each round (at the beginning of each new sequence, all money balances are reinitialized to zero for the sellers and 100 for the buyers). This target value is chosen so as to make inflation salient for the subjects over the limited amount of lab periods.

First transaction cost treatment: `noCost`:
The second treatment variable is the presence or absence of transaction costs. In a first treatment, denoted by `noCost`, we do not impose any transaction costs. In that treatment, the content of each package equals 100 chips to the buyer no matter the currency used or the quantity of packages purchased with each currency within or across rounds.

Second transaction cost treatment: `costs`: As a second treatment, denoted by `costs`, we impose transaction costs. In treatments with transaction costs, `costs`, the number of chips contained in a bought package (and its real world payoff) depends on which currency was used for the transaction and how many packages were already bought using this currency in that particular round. Packages bought using Dollars suffer increasing transaction costs within one round, where each additional package contains fewer chips, while packages bought using Bitcoins suffer a flat but substantial transaction cost. Specifically, for the treatment `costs`, the buyer receives the following number of chips for each bought package in a given round of a given sequence, depending on whether the package was bought using Bitcoin or Dollars, :

Packages (q_D respect. q_B)	1st	2nd	3rd	4rd	..	10th	11th	12th	⋯	19th and more
Chip content (purchase in dollar)	100	90	80	70	...	10	9	8	⋯	1
Chip content (purchase in bitcoin)	75	75	75	75	...	75	75	75	⋯	75

Table 4: Transaction costs per currency and trade volume. The chips content falls the more packages are purchased using Dollars. The chips content for Bitcoin-purchased packages remains at 75 no matter how many packages are bought using Bitcoin. When a buyer buys more than 3 packages using Dollars, the content falls below 70 chips, i.e. the Dollar transaction costs are higher when using Dollars rather than Bitcoin.

For instance, a buyer who purchases a first package using Dollars receives a package with 100 chips, whereas the second package he buys with Dollars in that round contains only $90 = \gamma(2) \times 100$ chips, etc. In the next trading round, the transaction costs are reset to zero for the first package bought with Dollars and 25 for the first package bought with Bitcoin. With the given transaction costs, we impose

Transaction costs	*Dollar inflation*	
	No: $m = 1$	Yes: $m = 1.3$
No:	6	6
Yes:	6	6

Table 5: Number of independent observations per treatment

the transaction cost ratio function given in equation (**??**). With each additional package bought using Dollars, the favorability of Dollars versus Bitcoin shrinks.

See that the chips content when using Dollars drops to, and then remains at one, as buyers buy more than 19 packages per round using Dollars.

The cut-off of 20 packages was never binding in practice: no subject in any treatment bought more than 16 packages in Dollar over a single trading round, for a maximum of 19 packages in both currencies combined. Recall that there are 6 sellers per round, each selling 5 packages, i.e. there are 30 packages in total for sale against Bitcoin and Dollars in each round. We observed only seven instances of trades in Dollar exceeding 10 packages per participant per round, out of $6 \times 32 \times 16 = 3,072$ individual trade outcomes in the whole experiment.[17]

5 Experimental Implementation

The experiment was programmed using oTree (Chen et al., 2016) and was run in-person at the CREED lab of the University of Amsterdam. All participants were students: about 60% in Economics and Business, and most of the rest in Social Sciences and Humanities, including Law. Among the students, 52% were female, about 60% came from Western or Eastern Europe and 30% from Asia, and participants were on average 22 year old. 90% of them declared being proficient in English, the language used in the experiment. Less than half of them declared a previous experience as a subject in a lab experiment. Most importantly, assignment to treatments was randomized across all these characteristics.[18] We collected data from six experimental economies for each of the four treatments; see Table 5. Therefore, a total of 24 experimental sessions corresponding to as many experimental economies were run with 12 subjects each (6 buyers and 6 sellers). Out of the 24 sessions, 12 sessions were run in spring 2022 and the remaining 12 in spring 2023. No subject participated more than once in the experiment to obtain independence of the 24 economies of one another.

The participants could first read the instructions to the experiment on the screen privately, at their own pace. Then, the experimenter read them aloud. The participants had to answer correctly a four-question quiz on the transaction costs, payoffs and currency supply about the treatment to which they were assigned to before entering the game.

The first two rounds of trading were training rounds to the participants. This allowed them to experience each of their two roles as buyers and sellers, and familiarize themselves with the trading interface (see Fig. 2). It was made clear to the participants that these first two rounds would not count towards

[17] 32 is the total number of rounds played by each economy, there are 6 sellers in each round for each economy, 4 treatments and six groups (economies) per treatment.

[18] The F-statistic of joint significance of the demographics on treatment assignments are, respectively, 2.00*, 0.69, 1.22 and 1.35 for Trs. `noInfl-noCost`, `noInfl-cost`, `infl-noCost` and `infl-cost`.

their earnings. After these two rounds, the first sequence of trading started and participants knew that they will play as many sequences as possible to fill up the time during which they had been recruited. The participants were recruited for 2:15 hours but sequences were repeated so as to fit a two-hour session. Further, the sessions typically did not exceed 1:50 hour to ensure that the end of the last sequence could not be anticipated by the subjects.[19] We chose the distribution of the number of periods of play so as to address the trade-off between the emulation of impatience with shorter sequences and the accommodation of learning inherent to experimentation with human subjects with longer sequences. We randomly drew the length of the sequences out of a geometric distribution with success parameter $\beta = 1/6$ for the first session and then repeated the same series of sequences for all groups to ensure comparability across sessions. As a result, we implemented the five following sequences: a training sequence of two periods for subjects to become familiar with the trading interface and their tasks without their decisions counting towards their earnings, followed by four sequences of play of seven, eleven, six and eight periods, for a total of 32 periods of actual play.

After the last sequence, a questionnaire collected demographics and elicited the participants' strategies and comments in an open-ended format. Payments were made anonymously *via* bank transfers by the financial administration of the University of Amsterdam. The first and the third sequences of play were randomly drawn to be paid out to the subjects who earned on average 13 euros for the experiment, with an standard deviation of two euros, excluding a nine euro show-up fee.

6 Experimental Results

We discuss the results along the two research questions stated at the end of Section 4.1: after looking at the overall market functioning in the experiment, we shed light on the dynamics of currency substitution when the Dollar money supply changes.

6.1 Market efficiency and currency hoarding

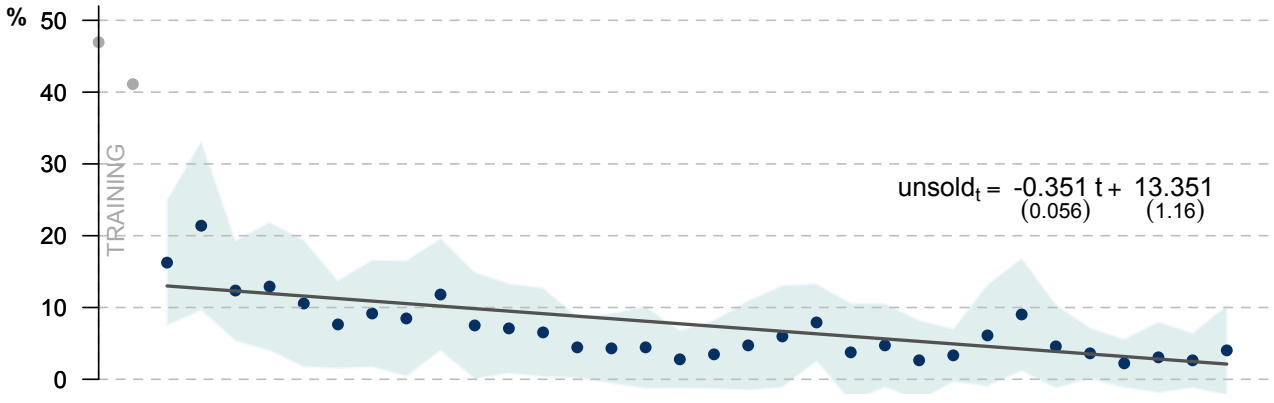
To develop measures of market efficiency, recall that only purchased packages are paid out to the subjects after the experiment ends. Money balances decay, and are not paid out to mimick the fact that Dollars and Bitcoins are fiat money. Furtherore, unsold packages perish after every round in the experiment, and are thus neither consumed nor paid out after the experiment. Thus, two metrics of market functioning are the amount of unsold packages of the sellers per round, and the realworld payoffs to the buyers that maps one-to-one to the utility derived from consumed chips packages. In the experiment, we find

Experimental results 6.1 (Market efficiency and currency hoarding) *Across all treatments,*

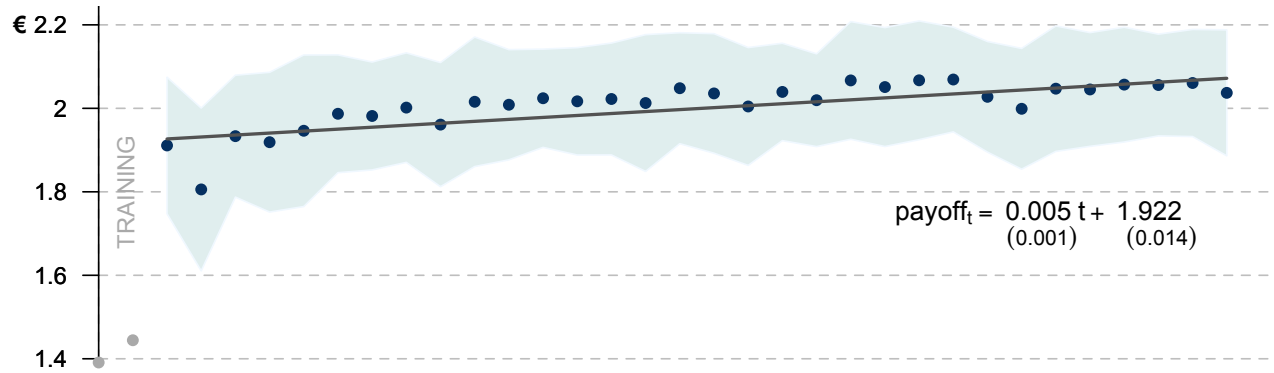
1. *the sellers' numbers of* ***unsold packages*** *per round decline across rounds and experimental sequences, yielding an increase in allocative efficiency of packages across trading sequences and rounds. Fewer unsold packages directly implies that the buyers attained* ***higher (real world) payoffs*** *across time since they consumed more packages.*
2. *we observe* ***persistent currency hoarding*** *across all rounds of trading. This either indicates precautionary savings where agents strategically hold back money or indicate rationing in the two goods*

[19] That is, the end of a sequence is kept in a distant enough future for the perception of the ending probability by the participants to remain constant throughout the session.

(a) Average unsold packages across sellers (both currency markets together)



(b) Average buyers' payoff



(c) Share of unspent currency balances (both currencies together)

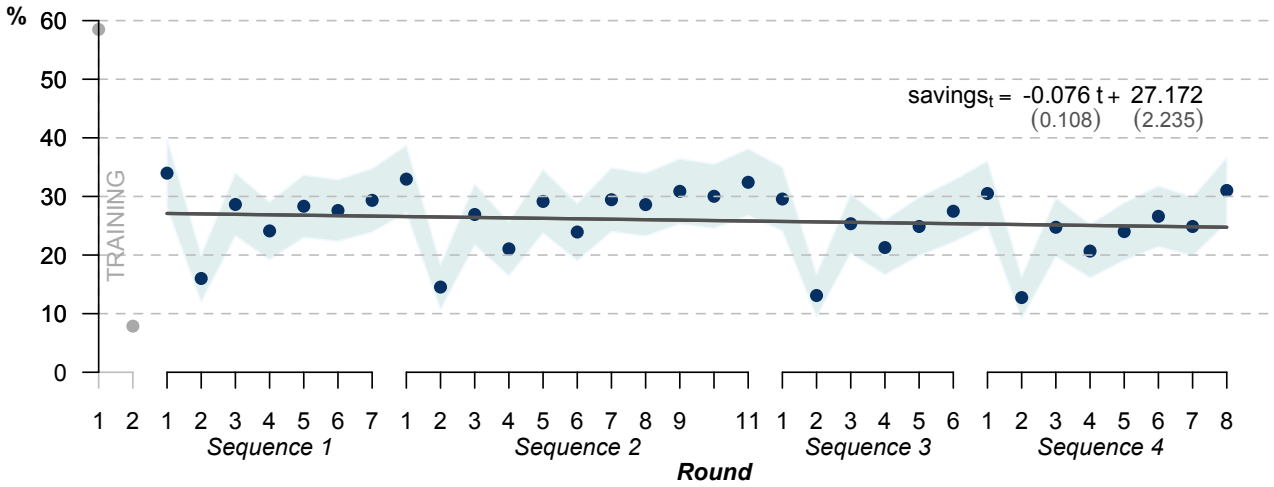


Figure 3: Efficiency over time averaged across all treatments over time. All experimental sessions and the two currency-specific goods markets are pooled together. The dots indicate the average per paid period. The shaded blue area indicate ± one standard deviation. The black line is the trend, represented by the linear regression line of the variable over the time period. The robust standard errors are reported between brackets underneath the estimated coefficients.

markets due to miscoordination between buyers and sellers. Currency hoarding indicates that Dollar and Bitcoin market prices of packages are too low relative to the case where money balances were entirely spent on goods each period.

Figures 3a and 3b report the evolution of these variables over time, by pooling together the two currency-specific markets and all experimental sessions. The top Figure 3a shows a significant decrease in unsold chips packages over time, down to a negligible amount of 5% of the total supply of packages

across experimental sessions.

Simultaneously with the decline in unsold packages, Figure 3b shows the rise of the buyers' payoffs across trading rounds and sequences, reaching an average of more than 2 euros per period.

The theory model predicts that because the chips packages perish, all the sellers' packages should be sold at any trading round. Moreover, because we hold the package endowments to the seller, and thus the package supply constant across trading rounds, the theory predicts that the real world payoff averaged across all buyers should be constant across rounds, even with monetary policy (but absent transaction costs). To compare the theoretical predictions to the experimental outcomes, our time series show that the experimental subjects increasingly learned how to maximize their real-world payoffs, yielding an increase in allocative efficiency across time, and approaching the theory-predicted outcome. In particular, the sellers learned that unsold packages lower their money balances in the next period when they are buyers, putting them at a disadvantage in comparison to the other buyers when bidding for packages.

Figure 3c shows the share of the buyers' unspent currency at the end of each period across trading sequences, for all treatments and markets pooled together. About 28% of money balances remain unspent across all rounds of trading, across all experimental sequences despite the fact that money balances are not paid out after the experiment. This currency hoarding can either be due to strategic behavior or rationing in the markets. Strategic behavior indicates precautionary savings where agents y hold back money today to insure against uncertain outcomes tomorrow (intertemporal substitution). Rationing can occur due to miscoordination between buyers and sellers, and because the markets open for only 90 seconds. If a buyer is too slow to make offers or adjust offer prices. the sellers may have sold their packages to other, faster buyers, possibly at too low prices. Miscoordination can occur because some sellers may decide to offer all of their packages in the Bitcoin denominated market, so that the buyers do not have the chance to spend their Dollar balances. Note that the experiment does not allow sellers to reallocate their packages across markets once the trading period starts. Thus, the sellers cannot react to unexpected market conditions from the buy side. In either case, currency hoarding implies that the Bitcoin and Dollar prices at which the chips packages were traded were too low relative to the market clearing price at which all currency had been exchanged for all packages, given that we observe nearly no unsold packages. The observed currency hoarding is remarkable because the experimental design imposed high impatience on the agents by applying a high termination probability of $1/6$ per round in every trading sequence. This termination probability corresponds to a discount factor as low as $5/6$. A high termination rate, i.e. high impatience implies that savings may not pay off in the next round, and should make the subjects reluctant to save.

The word cloud in Figure 5 reveals the subjects' self-reported behavior and strategies in the open-ended, post-experiment questionnaire. The figure reports a wordcloud of their answers by pooling all sessions together, where larger characters indicate more frequent mentioning. The self-reported strategies show an overall awareness and attention to the monetary incentives of the experimental tasks, with words such as 'currency' or 'money' being recurrent in the answers. The wordcloud clearly depicts market equilibration forces based on prices rather than goods quantities, using words such as "prices," "highest," and "lowest." The trading strategies also concern the timing of actions given the competition under strategic uncertainty and time pressure to sell and buy packages, with words related to both quick decision-making ("first," "fast," "quick," "started") and intentional delay ("wait," "later," "last," "keep," "end").

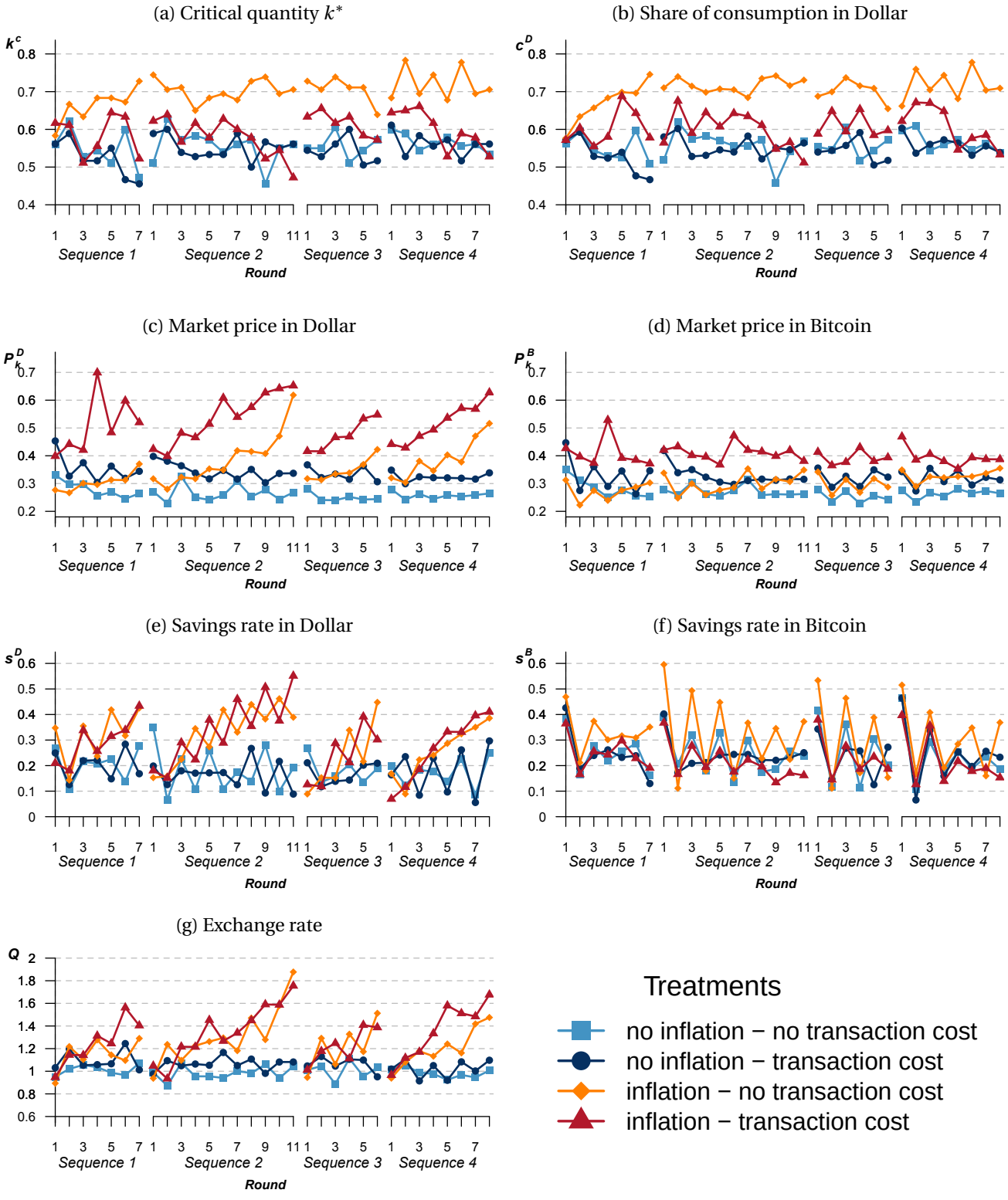


Figure 4: Average trade, price, and savings dynamics of each treatment

6.2 Monetary policy, and transaction costs with currency competition

We next analyze whether and how central bank transfers and transaction costs impact currency competition in the experiment. We first look at the aggregate dynamics in each experimental treatment and then estimate treatment-dependent asymptotic values of the main variables.

6.2.1 Aggregate dynamics in the experiment

For each of the four treatments, Figure 4 reports average changes of the critical quantity, the share of consumption purchased in Dollar, the average package market prices in Dollar and Bitcoin (weighted by quantities), the savings rates in each currency and the implicit exchange rate, i.e., the price of a Bitcoin in Dollars, across trading rounds and experimental sequences. Recall that each treatment was run with six independent groups, each group containing 12 subjects (6 buyers and 6 sellers). We next summarize our experimental findings, comparing behavior within and across treatments:

Experimental results 6.2 (Benchmark: no monetary policy, no transaction costs) *In the benchmark treatment without monetary policy and no transaction costs, we observe that*

1. *both currencies are used for goods purchases to an almost similar extent*
   (a) *the critical quantity k^*, i.e. the share of packages the sellers put for sale in the Dollar denominated market is relatively stable at 50-60%. That is, even though in the benchmark treatment Dollars and Bitcoins are perfect substitutes, the seller subjects slightly prefer receiving Dollar over Bitcoin, which reveals a "home bias" af the subjects, tending towards Dollars without any reason*
   (b) *the share of consumption the buyers purchase using Dollars is, therefore, likewise at 50-60%, since there are nearly no unsold packages. Note, it is the sellers who determine how many packages are offered for sale in either currency. Therefore, the difference in k^* and the consumption share in Dollars only stems from unsold packages. However, less than 10% of packages are unsold after the first trading sequence.*
2. *the package market prices in Dollar and Bitcoin are fairly stable, and similar both ranging at 25-30 Dollars, respectively Bitcoin.*
3. *some oscillation in the savings rates of Dollars and Bitcoins from round to round which is caused by the alternation of sellers and buyers. When comparing the savings rates across every other round, the savings rates in Dollars and Bitcoins are fairly stable.*
4. *the implicit exchange rate, i.e. the Bitcoin price in Dollars is fairly stable, and around one, yielding $Q_t/Q_{t+1} \approx 1$. This is in line with Kareken and Wallace (1981) who show that with perfect foresight, without monetary policy or transaction costs, the exchange rate is fixed across time.*

Experimental results 6.3 (with versus without Monetary policy) *Comparing the benchmark treatment (BT: no monetary policy and no transaction costs) with the monetary policy treatment (MPT: with monetary policy but no transaction costs) we observe*

1. *in the MPT treatment where the Dollar supply rises across time, more packages are sold for Dollars rather than Bitcoin, the critical quantity k^* is higher, relative to the BT benchmark treatment where the Dollar supply is left constant. That is, the inflationary money (good money) drives out the non-inflationary money as the medium of exchange, in line with Gresham's law. See, though, that in either treatment, the critical quantity is relatively stable across rounds, even though the MPT strictly raises the Dollar supply in each round.*
2. *in the MPT treatment where the Dollar supply rises across time, more packages are bought for Dollars rather than Bitcoin relative to the BT benchmark treatment. Therefore, the share of consumption purchased in Dollars is higher in the MP treatment than in the benchmark treatment. Note, if all packages are sold, the critical good and the sshare of consumption purchased in Dollars are equivalent.*

3. *the increase in the Dollar supply in the MPTreatment causes a rise in the Dollar package price level, and strong Dollar inflation relative to the benchmark treatment where the Dollar supply is left constant*
4. *the increase in the Dollar supply in the MPTreatment causes a rise in the Bitcoin package price level, but no Bitcoin inflation relative to the benchmark treatment where the Dollar supply is left constant*
5. *the increase in the Dollar supply in the MPTreatment causes a strong rise in the Dollar savings rate relative to the benchmark treatment where the Dollar supply is left constant.*
6. *Comparing the MPTreatment to the benchmark, the overall effect on the Dollar velocity is ambiguous because both the Dollar supply and the Dollar savings rate increase*
7. *the increase in the Dollar supply in the MPTreatment causes a decline in the Bitcoin savings rate relative to the benchmark treatment where the Dollar supply is left constant. This strictly raises the Bitcoin velocity, i.e., more Bitcoins of the total Bitcoin stock are used for purchases.*
8. *the increase in the Dollar supply in the MPTreatment causes a strict increase in the implicit Bitcoin exchange rate (Bitcoin deflation) across rounds relative to the benchmark treatment in which the exchange rate is fairly constant and around one. That is, Bitcoins become more and more valuable in every round relative to the Dollar,* $Q_t/Q_{t+1} < 1$.

All of these findings are very much in line with our theory predictions, formulated in the Monetary policy Hypothesis (3.3).

Experimental results 6.4 (with versus without transaction costs) *Comparing the benchmark treatment (BT: no monetary policy and no transaction costs) with the transaction cost treatment (TCT: without monetary policy but with transaction costs) we observe that*

1. *in the TCT treatment where transaction costs are imposed on Dollar and Bitcoin purchases, the number of packages sold for Dollars, i.e. the critical quantity* k^**, stays about the same relative to the benchmark treatment where no transaction costs are imposed. Likewise, the share of consumption purchased in Dollars remains about the same level in the treatment with transaction costs relative to the treatment without costs [no effect]*
2. *in the TCT treatment where transaction costs are imposed on Dollar and Bitcoin purchases, both the Dollar and the Bitcoin price levels for packages are higher relative to the benchmark treatment with no costs. This means, that the subjects paid more for packages with less content (in either currency) relative to the benchmark case. Yet, prices are stable at these higher levels, implying that there is hardly and Dollar or Bitcoin inflation across time.*
3. *the implicit Bitcoin exchange rate, the price of one Bitcoin in Dollars is only slightly higher, above one, in the TCT treatment relative to the benchmark treatment without costs. However, as in the benchmark, the exchange rate is fairly stable in the TCT, yielding* $Q_t/Q_{t+1} \approx 1$.

Experimental results 6.5 (Adding transaction costs to monetary policy) *Comparing the monetary policy treatment MPT (without transaction costs) to the monetary policy treatment with transaction costs MPTCT we observe that*

1. *adding transaction costs to the monetary policy treatment substantially reduces the critical quantity* k^**, i.e. the quantity of packages sold for Dollars versus Bitcoin. That is, despite a perpetual increase in the Dollar supply across rounds, the sellers are less willing to sell against Dollars and rather sell for Bitcoin, because the Dollar transaction costs are so substantial. Furthermore, the critical quantity*

declines across rounds in the MPTCT treatment wheras it is stable in the MPT without transaction costs. That is, fewer and fewer packages are offered for Dollars across rounds, since sellers preferred selling for Bitcoin. In line with this result, we see a substantial reduction in the buyers' consumption afforded by Dollar spending in the MPTCT relative to the MPT without transaction costs. Rather the subjects purchased packages using Bitcoin, and increasingly did so across rounds.

2. *adding transaction costs to the monetary policy treatment substantially increases the Dollar price level beyond the already increased Dollar price in the MPT, and preserves the Dollar inflation observed in the MPT. Adding transaction costs to the MPT also substantially increases the Bitcoin price level but leaves Bitcoin inflation flat, close to zero, as in the MPT.*
3. *adding transaction costs to the monetary policy treatment leaves the Dollar savings rate unchanged but reduces the Bitcoin savings rate.*
4. *adding transaction costs to the monetary policy treatment leaves the implicit Bitcoin exchange rate, the price of one Bitcoin in Dollars about same. That is, there is a substantial increase in the Bitcoin price across trading rounds (Bitcoin deflation), yielding* $Q_t/Q_{t+1} < 1$.

The comparison between the monetary policy treatment with versus without transaction costs is fairly striking since it demonstrates a decay of the Dollar as the dominant medium of exchange: when adding transaction costs, fewer and fewer goods are sold and purchased against Dollars across time, even though the Dollar balances of the subjects are increased by central bank transfers in each round. In some rounds, the critical quantity falls even below the benchmark case without monetary policy or transaction costs. The rationale is that due to the imposition of transaction costs, those many Dollars buy fewer and fewer chips content, so that spending Dollars on packages does not pay off in terms of a higher consumption. From the sellers perspective, this means that they rather sell against Bitcoin than Dollars, reallocating their packages across market. From the buyers' point of view, because fewer packages are offered against Dollars, and because the Dollar balances are rised by central bank transfers, the Dollar price level rises sharply, even stronger than in the case with just monetary policy. The Dollar savings rate is as high as in the MPT without transaction costs, which may indicate that the subjects are underestimating the central bank transfers or market clearing prices. The fact that the sellers offer more packages for Bitcoin should actually reduce the Bitcoin price level. The reduced savings rate for Bitcoin, however, may drive up or stabilize its price. Overall, while monetary policy via an increase in the Dollar supply can raise the Dollar's acceptance as a medium of exchange by increasing its relevance for purchases, Dollar transaction costs can undo this effect. Further, adding transaction costs on top of expansionary monetary policy can amplify the effect on Dollar and Bitcoin price levels.

Experimental results 6.6 (Adding monetary policy to transaction costs) *Comparing the transaction cost treatment TCT (without monetary policy) to the transaction cost treatment with monetary policy MPTCT we observe that*

1. *adding monetary policy to transaction costs slightly raises the critical quantity* k^**, i.e. the quantity of packages sold for Dollars versus Bitcoin, and raises the buyer's cosumption purchased with Dollars.*
2. *adding Dollar monetary policy to the transaction cost treatment substantially increases both the Dollar price and the Bitcoin price level. In addition it raises Dollar inflation but leaves Bitcoin inflation unchanged, and flat.*
3. *adding monetary policy to transaction costs strictly increases the Dollar savings rate across time but leaves the Bitcoin savings rate fairly unchanged*

4. *adding monetary policy to transaction costs strictly increases the Bitcoin exchange rate across time (Bitcoin deflation), the price of one Bitcoin in Dollars rises round per round,* $Q_t/Q_{t+1} < 1$.

Because the underlying model of the experiment admits equilibria with a constant critical good (and an adjustment to CB transfers via prices) as well as equilibria with a time-varying critical good (and an adjustment via currency substitution), we focus on identifying time variation in the main variables in the different treatments. The regression models reported in Table 6 reveal that the critical good decreases in all treatments but Tr. `infl-noCost`, and does so even more rapidly in Tr.`infl-cost` (Cols. I-II). Without costs, CB transfers leads to a higher critical good than without and this difference tends to increase over time. By contrast, under transaction costs, CB transfers produce a decrease in the critical good. Transaction costs do not affect the dynamics of the critical good in the absence of CB transfers.

The saving rate in Dollar (Cols. III-IV) and the Dollar price of a Bitcoin (Cols. VII-VIII) increase over time in the two treatments featuring CB transfers. Conversely, the saving rate in Bitcoin tends to decrease in all treatments (Col. V) and even more so in Tr.`infl-cost` (Col. VI). These different dynamics reflect the price stickiness pattern discussed above: as prices do not increase as fast as the CB inflation target, subjects accumulate Dollar currency holdings. They are also consistent with increasing trade volumes in Bitcoin in the presence of transaction costs and CB transfers, which leads to a faster decrease in the Bitcoin saving rate and a stronger hoarding on Dollar than in the three other treatments.

Dependent variable:	Critical good		Saving rate in Dollar		Saving rate in Bitcoin		Exchange rate		Exchange rate growth	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Treatment dummy [omitted: Tr. `noInfl-noCost`]										
Tr. `noInfl-Cost`	−0.014	−0.023	−0.015	−0.004	−0.018	−0.004	0.063**	0.056**	0.049*	0.017
	(0.022)	(0.026)	(0.021)	(0.020)	(0.026)	(0.026)	(0.029)	(0.028)	(0.028)	(0.032)
Tr. `infl-noCost`	0.114***	0.107***	−0.056	−0.048	0.067**	0.073**	−0.047	−0.069	−0.115***	−0.190***
	(0.024)	(0.025)	(0.040)	(0.040)	(0.032)	(0.032)	(0.070)	(0.080)	(0.037)	(0.045)
Tr. `infl-cost`	0.071***	0.079**	−0.084***	−0.087***	−0.002	0.020	−0.028	−0.022	−0.061**	−0.129***
	(0.026)	(0.031)	(0.023)	(0.026)	(0.028)	(0.034)	(0.052)	(0.058)	(0.027)	(0.022)
round	−0.005***	−0.006***	−0.002	0.0005	−0.013***	−0.012***	0.002	0.002	0.004	0.006
	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)	(0.002)	(0.005)	(0.006)	(0.006)	(0.006)
Tr. `noInfl-Cost`	0.001	0.002	0.002	−0.00004	0.003	0.001	0.001	0.002	−0.012*	−0.006
× round	(0.003)	(0.003)	(0.003)	(0.003)	(0.002)	(0.002)	(0.006)	(0.006)	(0.007)	(0.007)
Tr. `infl-noCost`	0.006**	0.007**	0.034***	0.033***	0.001	−0.001	0.060***	0.064***	0.023***	0.036***
× round	(0.003)	(0.004)	(0.005)	(0.005)	(0.001)	(0.002)	(0.020)	(0.021)	(0.009)	(0.010)
Tr. `infl-cost`	−0.008***	−0.008**	0.041***	0.041***	−0.004	−0.007*	0.072***	0.073***	0.015**	0.031***
× round	(0.002)	(0.003)	(0.002)	(0.003)	(0.003)	(0.004)	(0.013)	(0.014)	(0.007)	(0.007)
Constant	0.559***	0.566***	0.226***	0.205***	0.310***	0.318***	0.986***	0.994***	−0.052**	−0.144***
	(0.018)	(0.021)	(0.016)	(0.017)	(0.011)	(0.016)	(0.031)	(0.044)	(0.023)	(0.043)
R^2	0.324	0.375	0.343	0.478	0.088	0.168	0.351	0.413	0.031	0.451
Obs.	768	696	768	696	768	696	768	696	744	696
Controls	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes

Notes: OLS estimates. Clustered standard errors at the group level are reported between brackets. Dummy variables for the sequence number are always included; controls are the last two inflati
and in Bitcoin and the last two fractions of unsold goods in the two markets. *p<0.1; **p<0.05; ***p<0.01.

Table 6: Time variation in the main variable

6.2.2 Estimating the asymptotic values

We have uncovered significant time variation in the main variables of the experiment but the sequences of play have a limited number of rounds in the lab out of both practicability concerns and coherence with the underlying model that relies on the hypothesis of impatient agents. What would the behavior of the main variables of interest have been had each sequence continued for a much longer period? To shed light on the matter, we estimate the long-run or asymptotic values of these variables using a convergence assessment method inspired by Duffy et al. (2016).[20] Table 7 displays these estimates and reports on the cross-treatment comparisons.[21]

In the absence of CB transfers, transaction costs do not significantly affect trade and currency competition; a little more over half of the trade occurs in Dollar (Panels A and B), which is consistent with the optimal allocation of packages given the cost structure and assuming a constant critical good equilibrium. Moreover, subjects converge towards saving about 20% of their currency holdings (Panels C and D) and prices on both markets are constant (Panels D and E).

The situation is significantly different when CB transfers are introduced. In the absence of transaction costs, subjects then substitute Dollar purchases for Bitcoin trade and almost three quarters of the trade end up in Dollar. Because considerable price stickiness causes Dollar inflation to settle on a positive yet below-target rate, subjects accumulate Dollar and a high fraction of their Dollar endowment ends up unspent. Interestingly, Dollar inflation also triggers Bitcoin inflation, in line with the conclusions of the seminal model of Kareken and Wallace (1981) and their formulation of the Gresham's law. By contrast, in the presence of costs, CB transfers have the opposite effects on currency substitution: the fraction of trade in Dollar is driven down (almost three quarters of the trade would end up in Bitcoin) while subjects end up saving less and trading more in Bitcoin. This dynamics is in line with the prediction of the SU model. No matter the cost structure, there is increased difficulty in coordination among subjects, as reflected by the higher standard deviations in the presence than in the absence of inflation.

6.2.3 Diving into the individual market behaviors

[20] To be precise, for each time series of interest in each group, we estimate autoregressive processes with and without intercept and with up to two lags (to account for the alternating pattern of trade in the model and in the lab). We then select the first stationary model that minimizes the BIC information criterion. If no stationary model fits the data, the variable is said to converge to its upper limit or to diverge.

[21] Given the inherent difficulty of collecting many independent observations in group experiments involving each 12 subjects, it is sometimes not possible to disentangle a true null effect from a lack of statistical power.

		(1)	(2)	(1) vs. (2)	(3)	(4)	(3) vs. (4)
		Transaction costs			*Transaction costs*		
		No	*Yes*	$p-$value	*No*	*Yes*	$p-$value
		Panel A. Critical good			***Panel B. Share of consumption in Dollar***		
(I)	$\bar{\pi}=1$	0.548 (0.038)	0.548 (0.048)	0.818	0.550 (0.035)	0.465 (0.231)	0.937
(II)	$\bar{\pi}=1.3$	0.734 (0.143)	0.289 (0.317)	0.004^{***}	0.740 (0.139)	0.500 (0.248)	0.009^{***}
p-value (I) vs. (II)		0.004^{***}	0.387		0.002^{***}	0.418	
		Panel C. Saving rate in Dollar			***Panel D. Saving rate in Bitcoin***		
(I)	$\bar{\pi}=1$	0.180 (0.044)	0.172 (0.012)	0.485	0.232 (0.015)	0.232 (0.051)	0.937
(II)	$\bar{\pi}=1.3$	0.440 (0.151)	0.520 (0.194)	0.420	0.297 (0.082)	0.103 (0.119)	0.015^{**}
p-value (I) vs. (II)		0.002^{***}	0.002^{***}		0.145	0.067^{*}	
		Panel D. Inflation rate in Dollar			***Panel E. Inflation rate in Bitcoin***		
(I)	$\bar{\pi}=1$	0.002 (0.004)	0.0016 (0.025)	1.000	0.011 (0.027)	0.031 (0.044)	0.424
(II)	$\bar{\pi}=1.3$	0.204 (0.256)	0.070 (0.020)	0.329	0.066 (0.055)	0.005 (0.011)	0.061^{*}
p-value (I) vs. (II)		0.045^{**}	0.009^{***}		0.061^{*}	0.303	

Notes: Each cell reports the estimated mean of the stationary auto-regressive process of up to two lags that minimizes the BIC information criterion on each time series in each session, averaged over the six independent groups; standard deviations are reported next in parentheses. Similarly, each p-value corresponds to the exact two-sided Mann-Whitney rank-sum test of cross-treatment comparison, performed on matching-group level with six observations per treatment variable.

Table 7: Estimated asymptotic values of the main aggregate variables

Dependent variable	Bidding prices in Dollar			Bidding prices in Bitcoin			Consumption share in Dollar		
	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)
Treatment dummy [omitted: Tr. `noInfl-noCost`]									
Tr. `noInfl-cost`	0.16*	0.09	0.06*	0.06	0.09	0.09	0.12	0.10	0.12
	(0.10)	(0.08)	(0.03)	(0.08)	(0.09)	(0.07)	(0.09)	(0.10)	(0.08)
Tr. `infl-noCost`	−0.32	−0.43	−0.47**	0.07	0.07	−0.03	0.42***	0.31**	0.28**
	(0.28)	(0.28)	(0.23)	(0.16)	(0.15)	(0.10)	(0.11)	(0.14)	(0.12)
Tr. `infl-cost`	0.33**	0.24**	−0.06	0.46***	0.39***	0.19***	0.39***	0.31**	0.26**
	(0.15)	(0.12)	(0.07)	(0.09)	(0.10)	(0.07)	(0.10)	(0.14)	(0.12)
round	−0.003	−0.03***	−0.01**	−0.01*	−0.02***	−0.01**	−0.01	−0.003	−0.02*
	(0.01)	(0.01)	(0.01)	(0.004)	(0.004)	(0.003)	(0.01)	(0.01)	(0.01)
Tr. `noInfl-cost` × round	−0.02**	−0.02**	−0.01	−0.01	−0.01	−0.01	−0.01	−0.005	0.01
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Tr. `infl-noCost` × round	0.22***	0.16***	0.15***	0.03**	0.02*	0.03***	−0.003	−0.04*	−0.03
	(0.07)	(0.05)	(0.05)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.03)
Tr. `infl-cost` × round	0.15***	0.08***	0.10***	−0.01	−0.01	−0.002	−0.04***	−0.05**	−0.03
	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.02)
Intra-period order	−0.0000	−0.0002	−0.001	0.001	0.001	0.001			
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)			
Dollar balance $t-1$		0.06	0.02		−0.03***	−0.05***		−0.01	−0.02
		(0.04)	(0.05)		(0.01)	(0.01)		(0.03)	(0.04)
Bitcoin balance $t-1$		−0.003	−0.03		0.18***	0.14***		−0.33***	−0.27***
		(0.01)	(0.02)		(0.02)	(0.01)		(0.03)	(0.04)
Dollar profits $t-2$		0.25***	0.25***		0.03*	0.06***		0.29***	0.37***
		(0.03)	(0.03)		(0.02)	(0.02)		(0.04)	(0.04)
Bitcoin profits $t-2$		0.09**	0.11***		0.04**	0.07***		−0.20***	−0.17***
		(0.04)	(0.03)		(0.02)	(0.02)		(0.05)	(0.05)
Dollar spending $t-1$		−0.02	−0.10***		0.04***	−0.002		−0.0001	−0.02
		(0.02)	(0.02)		(0.01)	(0.01)		(0.02)	(0.02)
Bitcoin spending $t-1$		0.04***	−0.02		0.03***	−0.02**		−0.06***	−0.02
		(0.01)	(0.01)		(0.01)	(0.01)		(0.02)	(0.03)
Dollar inflation $t-1$		−0.45***	−0.12		−0.08	0.09		0.01	0.05*
		(0.08)	(0.15)		(0.10)	(0.09)		(0.02)	(0.02)
Bitcoin inflation $t-1$		0.20**	0.27**		−0.16**	−0.12**		−0.09***	−0.14***
		(0.08)	(0.11)		(0.06)	(0.06)		(0.02)	(0.03)

Dependent variable	Bidding prices in Dollar			Bidding prices in Bitcoin			Consumption share in Dollar		
	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)
Exchange rate in $t-1$		0.68^{***}	0.56^{***}		0.07	−0.09		-0.06^{***}	-0.07^{*}
		(0.16)	(0.17)		(0.10)	(0.11)		(0.02)	(0.04)
Dollar price $t-1$			0.004			0.01^{***}			0.001
			(0.003)			(0.002)			(0.002)
Dollar price $t-2$			0.31^{***}			0.17^{***}			−0.49
			(0.07)			(0.04)			(0.86)
Bitcoin price $t-1$			0.002			0.0002			-0.004^{**}
			(0.002)			(0.002)			(0.002)
Bitcoin price $t-2$			0.01^{***}			0.01^{***}			−0.002
			(0.002)			(0.002)			(0.002)
Constant	-0.88^{***}	-1.18^{***}	-1.14^{***}	-0.43^{***}	-0.47^{***}	-0.56^{***}	−0.28	0.15	0.43^{**}
	(0.20)	(0.16)	(0.15)	(0.13)	(0.16)	(0.16)	(0.20)	(0.14)	(0.20)
Observations	17,479	15,400	11,964	13,059	11,623	9,966	4,448	3,349	2,697
Adjusted R^2	0.26	0.33	0.38	0.06	0.13	0.18	0.04	0.42	0.31

Table 8: Buyers' behaviors (standardized regressions)

Dependent variable	Asking prices in Dollar			Asking prices in Bitcoin			Share sold in Dollar		
	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)
Treatment dummy [omitted: Tr. `noInfl-noCost`]									
Tr. `noInfl-cost`	−0.004	−0.01	−0.02	0.0001	0.002	−0.004	−0.03	−0.05	0.07
	(0.01)	(0.02)	(0.03)	(0.01)	(0.01)	(0.01)	(0.06)	(0.07)	(0.07)
Tr. `infl-noCost`	0.04	0.05	0.06	0.01	0.02	−0.01	0.31***	0.27***	0.30***
	(0.03)	(0.05)	(0.06)	(0.01)	(0.02)	(0.01)	(0.07)	(0.09)	(0.08)
Tr. `infl-cost`	0.01	−0.01	−0.05	0.01	0.02	−0.02	0.19***	0.18**	0.30***
	(0.01)	(0.02)	(0.04)	(0.01)	(0.02)	(0.01)	(0.07)	(0.09)	(0.07)
round	−0.002	−0.01	−0.01	−0.001	−0.0005	−0.0000	0.0005	−0.001	0.001
	(0.002)	(0.01)	(0.01)	(0.001)	(0.001)	(0.001)	(0.01)	(0.01)	(0.01)
Tr. `noInfl-cost` × round	−0.002*	−0.001	−0.001	−0.0001	−0.0003	0.0000	0.003	0.01	−0.001
	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)	(0.001)	(0.01)	(0.01)	(0.01)
Tr. `infl-noCost` × round	0.01**	0.01**	0.01	0.002	0.002	0.002	0.02**	0.01	0.003
	(0.003)	(0.003)	(0.005)	(0.001)	(0.001)	(0.002)	(0.01)	(0.02)	(0.02)
Tr. `infl-cost` × round	0.004***	0.01*	0.01*	−0.0002	0.001	0.001	−0.02***	−0.02	−0.03***
	(0.001)	(0.003)	(0.01)	(0.001)	(0.002)	(0.001)	(0.01)	(0.01)	(0.01)
Intra-period order	0.0001	0.0002	0.0003	0.0000	0.0000	0.0002*			
	(0.0001)	(0.0002)	(0.0003)	(0.0001)	(0.0001)	(0.0001)			
Dollar balance $t-1$		−0.01	−0.01		−0.001	−0.002		0.002	0.01
		(0.01)	(0.01)		(0.002)	(0.002)		(0.02)	(0.01)
Bitcoin balance $t-1$		0.02	0.04		−0.01**	−0.003**		−0.002	−0.02
		(0.03)	(0.04)		(0.003)	(0.001)		(0.02)	(0.02)
Dollar profits $t-2$		0.01	0.01		−0.002	−0.004		0.05**	0.11***
		(0.01)	(0.01)		(0.003)	(0.005)		(0.02)	(0.03)
Bitcoin profits $t-2$		−0.01	−0.02		0.005	−0.002		−0.14***	−0.12***
		(0.01)	(0.02)		(0.004)	(0.002)		(0.03)	(0.03)
Dollar spending $t-1$		0.001	−0.01		−0.002	−0.002***		0.05***	0.04**
		(0.01)	(0.01)		(0.001)	(0.001)		(0.02)	(0.02)
Bitcoin spending $t-1$		0.03	0.03		−0.004	−0.01**		−0.07***	−0.06***
		(0.03)	(0.04)		(0.002)	(0.002)		(0.02)	(0.02)
Dollar inflation $t-1$		−0.04	−0.04		0.01	−0.0003		0.01	0.03
		(0.03)	(0.03)		(0.01)	(0.01)		(0.01)	(0.02)
Bitcoin inflation $t-1$		−0.02	−0.02		0.003	0.02		−0.03***	−0.04**
		(0.03)	(0.03)		(0.01)	(0.02)		(0.01)	(0.02)

Dependent variable	Asking prices in Dollar			Asking prices in Bitcoin			Share sold in Dollar		
	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)
Exchange rate in $t-1$		0.02	0.01		-0.02^{*}	0.003		-0.06^{***}	-0.07^{***}
		(0.01)	(0.02)		(0.01)	(0.01)		(0.02)	(0.02)
Dollar price $t-1$			0.01^{*}			-0.0003			-0.72
			(0.01)			(0.003)			(0.78)
Dollar price $t-2$			-0.01			0.24			0.01^{***}
			(0.02)			(0.22)			(0.001)
Bitcoin price $t-1$			0.003^{**}			0.001^{***}			-0.002
			(0.001)			(0.0003)			(0.003)
Bitcoin price $t-2$			0.002^{**}			0.002^{**}			-0.002^{*}
			(0.001)			(0.001)			(0.001)
Constant	-0.03	-0.02	-0.13	-0.04	-0.03	-0.12^{***}	0.59^{***}	0.66^{***}	0.82^{***}
	(0.04)	(0.06)	(0.08)	(0.03)	(0.03)	(0.05)	(0.17)	(0.16)	(0.16)
Observations	17,691	15,204	12,269	13,098	11,456	10,003	4,608	3,456	2,851
Adjusted R^2	0.003	0.005	0.01	0.01	0.01	0.05	0.08	0.19	0.17

Table 9: Sellers' behaviors (standardized regressions)

	(1)	(2)	(1) vs. (2)	(3)	(4)	(3) vs. (4)
	Transaction costs			*Transaction costs*		
	No	*Yes*	$p-$value	*No*	*Yes*	$p-$value
	Panel A. Price paid in Market A			***Panel B. Price paid in Market B***		
(I) $\bar{\pi} = 1$	0.829 (0.162)	1.247 (0.110)	0.041**	1.040 (0.377)	1.900 (0.585)	0.093*
(II) $\bar{\pi} = 1.3$	2.153 (2.133)	1.502 (0.347)	0.589	1.951 (0.453)	1.394 (0.090)	0.310
p-value (I) vs. (II)	0.009***	0.589		0.026**	0.132	
	Panel C. Total chips consumption			***Panel D. Number of packages bought***		
(I) $\bar{\pi} = 1$	56.040 (135.881)	37.960 (60.462)	0.009***	0.569 (0.016)	0.524 (0.016)	0.699
(II) $\bar{\pi} = 1.3$	113.288 (4667.42)	54.756 (107.358)	0.026**	1.125(0.454)	0.780 (0.016)	0.700
p-value (I) vs. (II)	0.041**	0.026**		0.065*	0.015**	
	Panel E. Packages bought in Market A			***Panel E. Packages bought in Market B***		
(I) $\bar{\pi} = 1$	0.640 (0.030)	0.647 (0.018)	0.937	0.984 (0.046)	0.764 (0.026)	0.132
(II) $\bar{\pi} = 1.3$	1.395 (0.373)	0.972 (0.041)	0.180	1.056 (0.049)	0.890 (0.010)	0.240
p-value (I) vs. (II)	0.004***	0.015**		0.590	0.590	

Notes: Each cell reports the relative dispersion of a given variable across the six buyers for each treatment, averaged over the 32 paid periods and the six independent groups; standard deviations are reported next in parentheses. Each p-value corresponds to the exact two-sided Mann-Whitney rank-sum test of cross-treatment comparison, performed on matching-group level with six observations per treatment variable.

Table 10: Relative dispersion of buyers' prices and consumption levels



Figure 5: Word cloud of participants' self-reported strategies (post-experiment questionnaire)

6.3 Discussion

Discuss Benchmark versus Hypotheses As suggested by hypothesis (3.2), Dollar and Bitcoin prices for chips packags are fairly constant, and do not increase across time. The Bitcoin exchange rate is constant, as suggested by the theory. Recall that the exchange rate in $t = 0$, and thus relative prices in Dollars and Bitcoins are indetermined in $t = 0$. Only the change across time is pinned down in equilibrium. Furthermore, because Bitcoins and Dollars are perfect substitutes here, even highly asymmetric initial prices, and accordingly exchange rates away from one would be compatible with equilibrium.

Looking at the velocities, both the Bitcoin and the Dollar savings rates, and thus velocities are fairly constant across time. To see this note, that one must only compare the savings rates of every other period since the buyer and seller groups alternate. Comparing the savings rates at t to the savings rates at $t+1$ would mean to compare the savings of different agent groups.

Last, the critical quantity k^* denotes the share of the goods trade volume sold against Dollars,

$$k^* = \frac{\sum_i Y_{t,i}^D}{Y} \in [0,1] \tag{60}$$

Since k^* is mostly between 50-60% across sequences, slightly more than half of the goods are sold against Dollars, and slightly less than half of all goods are sold against Bitcoins. Note, since in the benchmark the currencies are perfect substitutes, any critical quantity k^* can arise as an equilibrium.

Relatedly, the consumption share in Dollars equals the share of the goods trade volume purchased using Dollars,

$$s^* = \frac{\sum_i q_{t,i}^D}{Y} \in [0,1] \tag{61}$$

The only difference between k^* and s^* is that some packages may end up unsold due to market miscoordination. Therefore, in the experiment, we always have $k^* \geq s^*$. Because unsold packages perish, and cannot be consumed in the next period, in equilibrium there are no unsold packages, and $k^* = s^*$.

In the benchmark treatment, we observe that $k^* = s^*$ pretty much.

MP with versus without costs Comparison of the monetary policy treatment with versus without transaction costs, note that

$$Y \equiv Y_t = m \frac{D_{t-1} V_t^{D,MP}}{P_t^{MP}} + \frac{B V_t^{B,MP}}{\hat{P}_t^{MP}} \tag{62}$$

$$> m\, r_t(q_t^D) \frac{D_{t-1} V_t^{D,MPTRa}}{P_t^{MPTRa}} + 0.75 \frac{B V_t^{B,MPTRa}}{\hat{P}_t^{MPTRa}} \tag{63}$$

which requires that

$$m D_{t-1} \left(\frac{V_t^{D,MP}}{P_t^{MP}} - r_t(q_t^D) \frac{V_t^{D,MPTRa}}{P_t^{MPTRa}} \right) + B \left(\frac{V_t^{B,MP}}{\hat{P}_t^{MP}} - 0.75 \frac{V_t^{B,MPTRa}}{\hat{P}_t^{MPTRa}} \right) > 0 \tag{64}$$

As analyzed in Schilling and Uhlig (2019a), if the central bank wants to implement an inflation target in a currency competition world of the Dollar to the Bitcoin, it may face challenges. The increase in the Dollar supply may not fully pass through into the Dollar price, or the Dollar velocity. Instead, there can be a shift in the relevance of the Dollar-denominated versus the Bitcoin-denominated package market since sellers can react to changes in the Dollar supply or prices by freely reallocating packages across markets. This market shift can cause Dollar monetary policy to impact the Bitcoin price and velocity in addition

to, or even instead of impacting the Dollar price. The following Hypothesis reflects these intricacies, and are reminiscent of the results in Schilling and Uhlig (2019a), even though our package markets are more segmented than theirs, as explained above.

7 Conclusions

Based on the theory contributions in Kareken and Wallace (1981); Schilling and Uhlig (2019a,b), this paper studies in theory and in the lab how supply-oriented Dollar monetary policy and currency-specific transaction costs impact the way the Dollar competes with an alternate central bank -independent currency, which we call Bitcoin.

In particular, we study how Dollar monetary policy and transaction costs affect how one currency crowds out the other in terms of the quantity of goods traded in each currency, and thus currency dominance.

The experimental results show that under currency competition, in line with the theory, an increase in the Dollar supply without adding transaction costs benefits the Dollar with regard to its dominance, i.e. total transaction volume, and preserves the traditional monetary policy channel between the Dollar supply and the Dollar price. However, transaction costs have strong effects on the economy, and weaken the Dollar's role as the dominant medium of exchange, by lowering the Dollar trade volume and amplifying Dollar inflation.

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A Appendix

A.1 Theoretical Analysis

A.1.1 Treatment: Benchmark

In the benchmark treatment, we have neither monetary policy nor transaction costs. We next analyze a green agent's optimization problem. A red agent's optimization is the same, with consumption shifted one time period ahead. Green agents are buyers and hence consume in even periods, and are sellers in odd periods. Let $\xi_t = 1$ when t is even, and zero when odd. The Lagrangian reads

$$
\begin{aligned}
L = \sum_{t=0}^{\infty} \xi_t \beta^t \Big[& u(c_t) + \lambda_{13,t}(\hat{P}_t q_t^B) + \hat{\lambda}_{13,t}(b_t - \hat{P}_t q_t^B) && (65)\\
& + \lambda_{14,t}(P_t q_t^D) + \hat{\lambda}_{14,t}(d_t - P_t q_t^D) && (66)\\
& + \lambda_{15,t}(q_t^D + q_t^B - c_t) && (67)\\
& + \lambda_{16,t}(b_t - \hat{P}_t q_t^B - b_{t+1}) && (68)\\
& + \lambda_{17,t}(d_t - P_t q_t^D - d_{t+1}) \Big] && (69)\\
+ (1-\xi_t)\beta^t \Big[& \lambda_{19,t}(y_t - x_t - z_t) && (70)\\
& + \lambda_{20,t}(b_t + \hat{P}_t x_t - b_{t+1}) && (71)\\
& + \lambda_{21,t}(d_t + P_t z_t - d_{t+1}) && (72)\\
& + \lambda_{22,t} x_t + + \lambda_{23,t} z_t \Big] && (73)
\end{aligned}
$$

The following first order conditions apply.If t is even and $t+1$ is odd,

$$
\begin{array}{lll}
I. & \frac{\partial L}{\partial c_t} & = u'(c_t) - \lambda_{15,t} = 0\\
II. & \frac{\partial L}{\partial q_t^D} & = \lambda_{14,t} P_t - \hat{\lambda}_{14,t} P_t + \lambda_{15,t} - \lambda_{17,t} P_t = 0\\
III. & \frac{\partial L}{\partial q_t^B} & = \lambda_{13,t} \hat{P}_t - \hat{\lambda}_{13,t} \hat{P}_t + \lambda_{15,t} - \lambda_{16,t} \hat{P}_t = 0\\
IV. & \frac{\partial L}{\partial x_{t+1}} & = -\lambda_{19,t+1} + \lambda_{20,t+1} \hat{P}_{t+1} + \lambda_{22,t+1} = 0\\
V. & \frac{\partial L}{\partial z_{t+1}} & = -\lambda_{19,t+1} + \lambda_{21,t+1} P_{t+1} + \lambda_{23,t+1} = 0\\
VI. & \frac{\partial L}{\partial b_t} & = \hat{\lambda}_{13,t} \beta^t + \lambda_{16,t} \beta^t - \lambda_{20,t-1} \beta^{t-1} = 0\\
VII. & \frac{\partial L}{\partial d_t} & = \hat{\lambda}_{14,t} \beta^t + \lambda_{17,t} \beta^t - \lambda_{21,t-1} \beta^{t-1} = 0\\
VIII. & \frac{\partial L}{\partial b_{t+1}} & = -\lambda_{16,t} \beta^t + \lambda_{20,t+1} \beta^{t+1} = 0\\
IX. & \frac{\partial L}{\partial d_{t+1}} & = -\lambda_{17,t} \beta^t + \lambda_{21,t+1} \beta^{t+1} = 0
\end{array}
\tag{74}
$$

Now assume that sellers sell some packages for both Bitcoins and Dollars in every period, i.e. $x_t > 0$ and $z_t > 0$ for all t. Assume, that a buyer buys some packages using Bitcoin and Dollars in every period, $q_t^D, q_t^B > 0$. Note, in equilibrium one implies the other. Then, market clearing prices P_t and $\hat{P}_t$ for packages denominated in Dollars and Bitcoin are well-defined. Moreover, $\lambda_{13,t} = \lambda_{14,t} = \lambda_{22,t} = \lambda_{23,t} = 0$. After solving for the Lagrange multipliers, the FOCs IV and V yield the Kareken Wallace result

$$
\frac{\hat{P}_{t+1}}{\hat{P}_t} = \frac{P_{t+1}}{P_t} \tag{75}
$$

i.e., the inflation rates on Dollars and Bitcoins must be the same, or, writing this equilibrium condition

in terms of the exchange rate $Q_t = P_t/\hat{P}_t$,

$$Q_{t+1} = Q_t \tag{76}$$

saying that the Bitcoin price denominated in Dollars must be constant across time. However, the initial exchange rate Q_0 is undetermined. Further, one obtains

$$0 \leq \hat{\lambda}_{14,t} = \frac{1}{P_t} u'(c_t) - \beta^2 \frac{1}{P_{t+2}} u'(c_{t+2}) \tag{77}$$

and

$$0 \leq \hat{\lambda}_{13,t} = \frac{1}{\hat{P}_t} u'(c_t) - \beta^2 \frac{1}{\hat{P}_{t+2}} u'(c_{t+2}) \tag{78}$$

If not all Bitcoin and Dollars are spent in every period, $\hat{P}_t q_t^B < b_t$ and $P_t q_t^D < d_t$,i.e. if there are savings, as we observe in the experiment, then $\hat{\lambda}_{13,t} = 0 = \hat{\lambda}_{14,t}$. In that case, FOC VIII and IX yield the consumption-Euler equations for consumption purchased in Bitcoins

$$\frac{\hat{P}_{t+2}}{\hat{P}_t} = \beta^2 \frac{u'(c_{t+2})}{u'(c_t)} \tag{79}$$

and Dollars

$$\frac{P_{t+2}}{P_t} = \beta^2 \frac{u'(c_{t+2})}{u'(c_t)}. \tag{80}$$

Market clearing In the benchmark model, we hold the Bitcoin and the Dollar supply constant across time. In equilibrium, clearing of both goods markets requires

$$\begin{aligned}
Y \equiv Y_t = 30 &= \sum_{i=1}^{6} y_{ti} && (81)\\
&= \sum_{i=1}^{6} c_{ti} + \sum_{i=1}^{6} \ell_{ti} && (82)\\
&= \sum_{i=1}^{6} (q_{ti}^D + q_{ti}^B) + \sum_{i=1}^{6} \ell_{ti} && (83)\\
&= \frac{\sum_{i=1}^{6} q_{ti}^D P_t}{P_t} + \frac{\sum_{i=1}^{6} q_{ti}^B \hat{P}_t}{\hat{P}_t} + \sum_{i=1}^{6} \ell_{ti} && (84)\\
&= \frac{D \sum_{i=1}^{6} q_{ti}^D P_t}{D P_t} + \frac{B \sum_{i=1}^{6} q_{ti}^B \hat{P}_t}{B \hat{P}_t} + \sum_{i=1}^{6} \ell_{ti} && (85)\\
&= \frac{D V_t^D}{P_t} + \frac{B V_t^B}{\hat{P}_t} + \sum_{i=1}^{6} \ell_{ti} && (86)\\
& && (87)
\end{aligned}$$

where we have defined the Dollar velocity as the share of Dollars spent in each period, $V_t^D = \frac{\sum_{i=1}^{6} q_{ti}^D P_t}{D}$, and the Bitcoin velocity as the share of Bitcoins spent per period, $V_t^B = \frac{\sum_{i=1}^{6} q_{ti}^B \hat{P}_t}{B}$. In equilibrium, the number of unsold packages is zero, $\sum_{i=1}^{6} \ell_{ti} = 0$ for any t.

Because we keep output Y constant across time, sequential market clearing requires

$$0 = Y_t - Y_{t+1} = D \left(\frac{V_t^D}{P_t} - \frac{V_{t+1}^D}{P_{t+1}} \right) + B \left(\frac{V_t^B}{\hat{P}_t} - \frac{V_{t+1}^B}{\hat{P}_{t+1}} \right) \tag{88}$$

From above, in any equilibrium it holds $Q_{t+1} = Q_t = Q_1$, and thus

$$\hat{P}_{t+1} = P_{t+1} \frac{\hat{P}_t}{P_t} = P_{t+1} \frac{\hat{P}_1}{P_1} \tag{89}$$

That is, because of the constancy of the exchange rate, I change in the Dollar price P_{t+1} uniquely determines the change in the Bitcoin price $\hat{P}_{t+1}$. Replacing $\hat{P}_{t+1}$ in (88),

$$0 = Y_1 - Y_{t+1} = D\left(\frac{V_1^D}{P_1} - \frac{V_{t+1}^D}{P_{t+1}}\right) + B\left(\frac{V_1^B}{\hat{P}_1} - \frac{V_{t+1}^B}{\hat{P}_{t+1}}\right) \tag{90}$$

$$= D\left(\frac{V_1^D}{P_1} - \frac{V_{t+1}^D}{P_{t+1}}\right) + \frac{B}{\hat{P}_1}\left(V_1^B - \frac{V_{t+1}^B P_1}{P_{t+1}}\right) \tag{91}$$

Market clearing says, that an increase in the Dollar price P_{t+1} (and thus increase in the Bitcoin price according to (89)) either requires an increase in the Dollar velocity V_{t+1}^D (Dollar savings reduction) or an increase in the Bitcoin velocity V_{t+1}^B (Bitcoin savings reduction), or both.

If not all Bitcoins and Dollars are spent in every period (which we observe in the experiment), in a symmetric equilibrium it holds $c_{ti} = y_{ti} = y_{t+2,i} = c_{t+2,i}$, thus

$$\frac{\hat{P}_{t+2}}{\hat{P}_t} = \beta^2 \frac{u'(c_{t+2})}{u'(c_t)} = \beta^2 \tag{92}$$

$$\frac{P_{t+2}}{P_t} = \beta^2 \frac{u'(c_{t+2})}{u'(c_t)} = \beta^2 \tag{93}$$

since in a symmetric equilibrium, $c_{t+2} = y_{t+2} = 5 = y_t = c_t$. Thus, we require

$$\hat{P}_{t+2} = \beta^2 \hat{P}_t \leq \hat{P}_t \tag{94}$$

$$P_{t+2} = \beta^2 P_t \leq P_t \tag{95}$$

In short, if the agents save some Bitcoins and Dollars across periods, the prices should weakly decline.

If all Bitcoins and Dollars are spent, market clearing yields that the prices must be constant across time:

$$\frac{5 - z_{ti}}{z_{ti}} = \frac{y_{ti} - z_{ti}}{z_{ti}} = \frac{x_{ti}}{z_{ti}} = \frac{q_{t,i}^B}{q_{ti}^D} \tag{96}$$

$$= \frac{b_t}{\hat{P}_t} \frac{P_t}{d_t} \tag{97}$$

$$= \frac{b_t^B}{\hat{P}_{t+1}} \frac{P_{t+1}}{d_t^B} \tag{98}$$

$$= \frac{b_{t+1}^S}{\hat{P}_{t+1}} \frac{P_{t+1}}{d_{t+1}^S} \tag{99}$$

$$= \frac{q_{t+1,i}^B}{q_{t+1,i}^D} \tag{100}$$

$$= \frac{y_{t+1,i} - z_{t+1,i}}{z_{t+1,i}} = \frac{5 - z_{t+1,i}}{z_{t+1,i}} \tag{101}$$

Here, $\frac{q_{t,i}^B}{q_{ti}^D} = \frac{b_t}{\hat{P}_t} \frac{P_t}{d_t}$ holds because buyers spend all Dollars and Bitcoins, then we use constancy of the

exchange rate, and then use that since all buyers spent all currency, the sellers of that period obtain all currency to spend as buyers in the next period. The equality above yields that $z_t = z_{t+1}$ is constant, thus $x_t = x_{t+1}$ is constant, thus q_t^B and q_t^D are constant, which finally yields that the Bitcoin price $\hat{P}_{t+1} = \hat{P}_1$ for packages is constant, as is the Dollar price, $P_t = P_1$ is constant.

A.1.2 Treatment: Monetary Policy (no Transaction costs)

With monetary policy, the central bank multiplies every Dollar in the economy with the multiplier m per period. In the experiment, $m = 1.3$, but we hold m general in the calculations here. The green agent's optimization problem changes with regard to the Dollar balances. Green agents are buyers and hence consume in even periods, and are sellers in odd periods. As before, let $\xi_t = 1$ when t is even, and zero when odd. The green agent's Lagrangian reads

$$
\begin{aligned}
L = \sum_{t=0}^{\infty} \xi_t \beta^t \Big[& u(c_t) + \lambda_{13,t}(\hat{P}_t q_t^B) + \hat{\lambda}_{13,t}(b_t - \hat{P}_t q_t^B) && (102)\\
& + \lambda_{14,t}(P_t q_t^D) + \hat{\lambda}_{14,t}(d_t - P_t q_t^D) && (103)\\
& + \lambda_{15,t}(q_t^D + q_t^B - c_t) && (104)\\
& + \lambda_{16,t}(b_t - \hat{P}_t q_t^B - b_{t+1}) && (105)\\
& + \lambda_{17,t}(m(d_t - P_t q_t^D) - d_{t+1}) \Big] && (106)\\
+ (1-\xi_t)\beta^t \Big[& \lambda_{19,t}(y_t - x_t - z_t) && (107)\\
& + \lambda_{20,t}(b_t + \hat{P}_t x_t - b_{t+1}) && (108)\\
& + \lambda_{21,t}(m(d_t + P_t z_t) - d_{t+1}) && (109)\\
& + \lambda_{22,t} x_t + + \lambda_{23,t} z_t \Big] && (110)
\end{aligned}
$$

The following first order conditions apply.If t is even and $t+1$ is odd,

$$
\begin{array}{lll}
I. & \frac{\partial L}{\partial c_t} & = u'(c_t) - \lambda_{15,t} = 0\\
II. & \frac{\partial L}{\partial q_t^D} & = \lambda_{14,t} P_t - \hat{\lambda}_{14,t} P_t + \lambda_{15,t} - \lambda_{17,t} P_t\, m = 0\\
III. & \frac{\partial L}{\partial q_t^B} & = \lambda_{13,t}\hat{P}_t - \hat{\lambda}_{13,t}\hat{P}_t + \lambda_{15,t} - \lambda_{16,t}\hat{P}_t = 0\\
IV. & \frac{\partial L}{\partial x_{t+1}} & = -\lambda_{19,t+1} + \lambda_{20,t+1}\hat{P}_{t+1} + \lambda_{22,t+1} = 0\\
V. & \frac{\partial L}{\partial z_{t+1}} & = -\lambda_{19,t+1} + \lambda_{21,t+1} P_{t+1}\, m + \lambda_{23,t+1} = 0\\
VI. & \frac{\partial L}{\partial b_t} & = \hat{\lambda}_{13,t}\beta^t + \lambda_{16,t}\beta^t - \lambda_{20,t-1}\beta^{t-1} = 0\\
VII. & \frac{\partial L}{\partial d_t} & = \hat{\lambda}_{14,t}\beta^t + \lambda_{17,t}\beta^t\, m - \lambda_{21,t-1}\beta^{t-1} = 0\\
VIII. & \frac{\partial L}{\partial b_{t+1}} & = -\lambda_{16,t}\beta^t + \lambda_{20,t+1}\beta^{t+1} = 0\\
IX. & \frac{\partial L}{\partial d_{t+1}} & = -\lambda_{17,t}\beta^t + \lambda_{21,t+1}\beta^{t+1}\, m = 0
\end{array}
\qquad (111)
$$

As before, assume that sellers sell some packages for both Bitcoins and Dollars in every period, i.e. $x_t > 0$ and $z_t > 0$ for all t. Assume, that a buyer buys some packages using Bitcoin and Dollars in every period, $q_t^D, q_t^B > 0$. Note again, in equilibrium one implies the other since sellers cannot sell if buyers do not buy. Then, market clearing prices P_t and $\hat{P}_t$ for packages denominated in Dollars and Bitcoin are well-defined, and $\lambda_{13,t} = \lambda_{14,t} = \lambda_{22,t} = \lambda_{23,t} = 0$. Solving for the Lagrange multipliers, the FOCs IV and V

yield a deviation from the Kareken Wallace result,

$$\frac{P_{t+1}}{P_t} = m \frac{\hat{P}_{t+1}}{\hat{P}_t} \tag{112}$$

i.e., the inflation rates on Dollars, on the left, must equal the Bitcoin inflation rate times the Dollar multiplier m, at any point in time. Put differently, from one period to the other, the Dollar inflation is m times larger than the Bitcoin inflation. Writing this equilibrium condition in terms of the exchange rate, We have

$$Q_{t+1} = m\, Q_t \tag{113}$$

saying that the Bitcoin price denominated in Dollars must increase by factor m across time. The initial exchange rate Q_0 remains undetermined, as in Kareken Wallace. Further, one obtains

$$0 \leq \hat{\lambda}_{14,t} = \frac{1}{P_t} u'(c_t) - \beta^2 m^2 \frac{1}{P_{t+2}} u'(c_{t+2}) \tag{114}$$

and

$$0 \leq \hat{\lambda}_{13,t} = \frac{1}{\hat{P}_t} u'(c_t) - \beta^2 \frac{1}{\hat{P}_{t+2}} u'(c_{t+2}) \tag{115}$$

If not all Bitcoind and Dollars are spent in every period, $\hat{P}_t q_t^B < b_t$ and $P_t q_t^D < d_t$,i.e. if there are savings, as we observe in the experiment, then $\hat{\lambda}_{13,t} = 0 = \hat{\lambda}_{14,t}$. In that case, FOC VIII and IX yield the consumption-Euler equations for consumption purchased in Bitcoins

$$\frac{\hat{P}_{t+2}}{\hat{P}_t} = \beta^2 \frac{u'(c_{t+2})}{u'(c_t)} \tag{116}$$

and Dollars

$$\frac{P_{t+2}}{P_t} = \beta^2 m^2 \, \frac{u'(c_{t+2})}{u'(c_t)}. \tag{117}$$

Market clearing In the Monetary policy treatment, we hold the Bitcoin supply constant, and the Dollar supply grows at rate m, $D_t = mD_{t-1}$. From above, in equilibrium, clearing of both goods markets requires

$$Y \equiv Y_t = 30 = \sum_{i=1}^{6} y_{ti} = \frac{D_t V_t^D}{P_t} + \frac{B V_t^B}{\hat{P}_t} + \sum_{i=1}^{6} \ell_{ti} \tag{118}$$

$$= m \frac{D_{t-1} V_t^D}{P_t} + \frac{B V_t^B}{\hat{P}_t} + \sum_{i=1}^{6} \ell_{ti} \tag{119}$$

In equilibrium, the number of unsold packages is zero, $\sum_{i=1}^{6} \ell_{ti} = 0$ for any t. Because output Y is constant across time, sequential market clearing requires

$$0 = Y_t - Y_{t+1} = D_t \left(\frac{V_t^D}{P_t} - \frac{m V_{t+1}^D}{P_{t+1}} \right) + B \left(\frac{V_t^B}{\hat{P}_t} - \frac{V_{t+1}^B}{\hat{P}_{t+1}} \right) \tag{120}$$

From above, in any equilibrium it holds $Q_{t+1} = m\, Q_t = m^t\, Q_1$, and thus

$$\hat{P}_{t+1} = \frac{1}{m} \, P_{t+1} \, \frac{\hat{P}_t}{P_t} = \frac{1}{m^t} \, P_{t+1} \, \frac{\hat{P}_1}{P_1} \tag{121}$$

Replacing $\hat{P}_{t+1}$ in the sequential market clearing constraint, (88),

$$0 = Y_1 - Y_{t+1} = D_1 \left(\frac{V_1^D}{P_1} - \frac{m^t V_{t+1}^D}{P_{t+1}} \right) + B \left(\frac{V_1^B}{\hat{P}_1} - \frac{V_{t+1}^B}{\hat{P}_{t+1}} \right) \tag{122}$$

$$= D_1 \left(\frac{V_1^D}{P_1} - \frac{m^t V_{t+1}^D}{P_{t+1}} \right) + \frac{B}{\hat{P}_1} \left(V_1^B - \frac{m^t V_{t+1}^B P_1}{P_{t+1}} \right) \tag{123}$$

If not all Bitcoins and Dollars are spent in every period (which we observe in the experiment), in a symmetric equilibrium it holds $c_{ti} = y_{ti} = y_{t+2,i} = c_{t+2,i}$, and thus

$$\frac{\hat{P}_{t+2}}{\hat{P}_t} = \beta^2 \frac{u'(c_{t+2})}{u'(c_t)} = \beta^2 \tag{124}$$

$$\frac{P_{t+2}}{P_t} = \beta^2 m^2 \frac{u'(c_{t+2})}{u'(c_t)} = \beta^2 m^2 \tag{125}$$

Thus, we require

$$\hat{P}_{t+2} = \beta^2 \hat{P}_t \leq \hat{P}_t \tag{126}$$

$$P_{t+2} = \beta^2 m^2 P_t \tag{127}$$

That is, the Bitcoin price should weakly decline. But the Dollar price may increase across time if $\beta m > 1$, i.e. if m is large enough. In the experiment, this is clearly the case.

If all Bitcoins and Dollars are spent, in a symmetric equilibrium, $d_{t+1} = m d_t$, thus, market clearing and monetary policy yield

$$\frac{5 - z_{ti}}{z_{ti}} = \frac{y_{ti} - z_{ti}}{z_{ti}} = \frac{x_{ti}}{z_{ti}} = \frac{q_{t,i}^B}{q_{ti}^D} \tag{128}$$

$$= \frac{b_t}{\hat{P}_t} \frac{P_t}{d_t} \tag{129}$$

$$= \frac{1}{m} \frac{b_t^B}{\hat{P}_{t+1}} \frac{P_{t+1}}{d_t^B} \tag{130}$$

$$= \frac{b_{t+1}^S}{\hat{P}_{t+1}} \frac{P_{t+1}}{d_{t+1}^S} \tag{131}$$

$$= \frac{q_{t+1,i}^B}{q_{t+1,i}^D} \tag{132}$$

$$= \frac{y_{t+1,i} - z_{t+1,i}}{z_{t+1,i}} = \frac{5 - z_{t+1,i}}{z_{t+1,i}} \tag{133}$$

since m cancels out. Thus, spending of all Dollars and Bitcoins implies that prices must be constant since the increase in the Dollar balances cancels out the increase in the Dollar price of packages.

A.1.3 Treatment: Transaction costs (no Monetary Policy)

We next introduce transaction costs. As a consequence, the number of packages purchased using Dollars and Bitcoins no longer equals consumption afforded using Dollars and Bitcoins. If an agent buys q_t^D packages using Dollars, she will consume $r_t(q_t^D)\, q_t^D$ chips packages, where $r_t(q_t^D) \leq 1$ is the marginal package content after transaction costs, and is a function that is decreasing in the number of packages purchased with Dollars. Here $1 - r_t(q_t^D)$ is the quantity dependent transaction cost for Dollars. We pin

down $r_t(q_t^D)$ in the main text above. Likewise, if an agent buys q_t^B packages using Dollars, she will consume $0.75\,q_t^D$ chips packages, and the remaining share of 0.25 packages is lost due to frictions. Importantly, the cost per package remains at P_t for Dollar purchases and $\hat{P}_t$ for Bitcoin purchases, no matter the quantity purchased using that currency.

We analyze again green agent's optimization problem. A red agent's optimization is the same, with consumption shifted one time period ahead. Green agents are buyers and hence consume in even periods, and are sellers in odd periods. Let $\xi_t = 1$ when t is even, and zero when odd. The Lagrangian reads

$$
\begin{aligned}
L = \sum_{t=0}^{\infty} \xi_t \beta^t \Big[& u(c_t) + \lambda_{13,t}(\hat{P}_t q_t^B) + \hat{\lambda}_{13,t}(b_t - \hat{P}_t q_t^B) && (134)\\
& + \lambda_{14,t}(P_t q_t^D) + \hat{\lambda}_{14,t}(d_t - P_t q_t^D) && (135)\\
& + \lambda_{15,t}(r_t(q_t^D)\, q_t^D + 0.75\, q_t^B - c_t) && (136)\\
& + \lambda_{16,t}(b_t - \hat{P}_t q_t^B - b_{t+1}) && (137)\\
& + \lambda_{17,t}(d_t - P_t q_t^D - d_{t+1}) \Big] && (138)\\
+ (1-\xi_t)\beta^t \Big[& \lambda_{19,t}(y_t - x_t - z_t) && (139)\\
& + \lambda_{20,t}(b_t + \hat{P}_t x_t - b_{t+1}) && (140)\\
& + \lambda_{21,t}(d_t + P_t z_t - d_{t+1}) && (141)\\
& + \lambda_{22,t} x_t + + \lambda_{23,t} z_t \Big] && (142)
\end{aligned}
$$

Define the short-cut

$$
R(q_t^D) \equiv \left(\frac{\partial r_t}{\partial q_t^D} \right) q_t^D + r_t(q_t^D), \tag{143}
$$

which denotes the increase in Dollar-afforded consumption when buying an additional package using Dollars. If t is even and $t+1$ is odd,

$$
\begin{array}{lll}
I. & \frac{\partial L}{\partial c_t} = u'(c_t) - \lambda_{15,t} & = 0\\
II. & \frac{\partial L}{\partial q_t^D} = \lambda_{14,t} P_t - \hat{\lambda}_{14,t} P_t + R(q_t^D)\,\lambda_{15,t} - \lambda_{17,t} P_t & = 0\\
III. & \frac{\partial L}{\partial q_t^B} = \lambda_{13,t} \hat{P}_t - \hat{\lambda}_{13,t} \hat{P}_t + 0.75\,\lambda_{15,t} - \lambda_{16,t} \hat{P}_t & = 0\\
IV. & \frac{\partial L}{\partial x_{t+1}} = -\lambda_{19,t+1} + \lambda_{20,t+1} \hat{P}_{t+1} + \lambda_{22,t+1} & = 0\\
V. & \frac{\partial L}{\partial z_{t+1}} = -\lambda_{19,t+1} + \lambda_{21,t+1} P_{t+1} + \lambda_{23,t+1} & = 0\\
VI. & \frac{\partial L}{\partial b_t} = \hat{\lambda}_{13,t} \beta^t + \lambda_{16,t} \beta^t - \lambda_{20,t-1} \beta^{t-1} & = 0\\
VII. & \frac{\partial L}{\partial d_t} = \hat{\lambda}_{14,t} \beta^t + \lambda_{17,t} \beta^t - \lambda_{21,t-1} \beta^{t-1} & = 0\\
VIII. & \frac{\partial L}{\partial b_{t+1}} = -\lambda_{16,t} \beta^t + \lambda_{20,t+1} \beta^{t+1} & = 0\\
IX. & \frac{\partial L}{\partial d_{t+1}} = -\lambda_{17,t} \beta^t + \lambda_{21,t+1} \beta^{t+1} & = 0
\end{array} \tag{144}
$$

As before, assuming that sellers sell some packages for both Bitcoins and Dollars in every period, i.e. $x_t > 0$ and $z_t > 0$ for all t, and that a buyer buys some packages using Bitcoin and Dollars in every period, $q_t^D, q_t^B > 0$, it holds $\lambda_{13,t} = \lambda_{14,t} = \lambda_{22,t} = \lambda_{23,t} = 0$. After solving for the Lagrange multipliers, the FOCs IV and V yield

$$
0.75\,\frac{P_{t+1}}{P_t} = R(q_t^D)\,\frac{\hat{P}_{t+1}}{\hat{P}_t}. \tag{145}
$$

That is, the Dollar inflation times the marginal consumption after Bitcoin transaction costs must equal

the Bitcoin inflation times the marginal consumption after Dollar transaction costs. Thus, an increase of the Dollar transaction costs (decrease in $R(q_t^D)$) either lowers the Dollar inflation or raises the Bitcoin inflation. Vice versa, a raise of the Bitcoin transaction costs (lowering 0.75 towards zero) either increases the Dollar inflation or lowers the Bitcoin inflation, in equilibrium. The transaction costs in a currency undoes the inflation in that currency.

Writing this equilibrium condition in terms of the exchange rate, we obtain

$$Q_{t+1} = \frac{R(q_t^D)}{0.75} Q_t \tag{146}$$

a higher marginal Dollar transaction cost (lower R) lowers the Bitcoin exchange rate across time whereas a higher marginal Bitcoin exchange rate increases the Bitcoin exchange rate. The initial exchange rate Q_0 remains undetermined. One obtains

$$0 \leq \hat{\lambda}_{14,t} = \frac{1}{P_t} u'(c_t) R(q_t^D) - \beta^2 \frac{1}{P_{t+2}} u'(c_{t+2}) R(q_{t+2}^D) \tag{147}$$

and

$$0 \leq \hat{\lambda}_{13,t} = \frac{0.75}{\hat{P}_t} u'(c_t) - \beta^2 \frac{0.75}{\hat{P}_{t+2}} u'(c_{t+2}) \tag{148}$$

If not all Bitcoind and Dollars are spent in every period, $\hat{P}_t q_t^B < b_t$ and $P_t q_t^D < d_t$,i.e. if there are savings, as we observe in the experiment, then $\hat{\lambda}_{13,t} = 0 = \hat{\lambda}_{14,t}$. In that case, FOC VIII and IX yield the consumption-Euler equations for consumption purchased in Bitcoins

$$\frac{\hat{P}_{t+2}}{\hat{P}_t} = \beta^2 \frac{u'(c_{t+2})}{u'(c_t)}. \tag{149}$$

Since the marginal Bitcoin transaction cost is contant in the number of packages purchased, it cancels out and does not affect the pricing equation. For Dollars,

$$\frac{P_{t+2}}{P_t} = \beta^2 \frac{R(q_{t+2}^D)}{R(q_t^D)} \frac{u'(c_{t+2})}{u'(c_t)}. \tag{150}$$

the transaction costs do affect the pricing equation.

Market clearing with transaction costs means that aggregate consumption is below the aggregate production, due to frictions. We hold the Bitcoin and the Dollar supply constant across time. We slightly adjust the notation here and let q_t^D the number of packages bought with Dollars, whereas $r_t(q_t^D) q_t^D$ is the consumption afforded with Dollars after accounting for transaction costs. Likewise, let q_t^B the number of packages bought with Bitcoins, whereas $0.75 q_t^B$ is the consumption afforded with Bitcoins after accounting for transaction costs. We define the aggregate transaction costs as

$$\sum_{i=1}^{6} TraCo_{ti} = \sum_{i=1}^{6} (1 - r_t(q_{ti}^D))\, q_{ti}^D + 0.25 q_{ti}^B \tag{151}$$

In equilibrium, clearing of both goods markets requires

$$Y \equiv Y_t = 30 = \sum_{i=1}^{6} y_{ti} \tag{152}$$

$$= \sum_{i=1}^{6} c_{ti} + \sum_{i=1}^{6} TraCo_{ti} + \sum_{i=1}^{6} \ell_{ti} \tag{153}$$

$$= \sum_{i=1}^{6} \left(r_t(q_{ti}^D)\, q_{ti}^D + 0.75\, q_{ti}^B\right) + \sum_{i=1}^{6} \left(1 - r_t(q_{ti}^D)\right) q_{ti}^D + 0.25 q_{ti}^B + \sum_{i=1}^{6} \ell_{ti} \tag{154}$$

$$= \frac{D \sum_{i=1}^{6} r_t(q_{ti}^D)\, q_{ti}^D P_t}{D P_t} + \frac{B \sum_{i=1}^{6} 0.75\, q_{ti}^B \hat{P}_t}{B \hat{P}_t} + \sum_{i=1}^{6} \left(1 - r_t(q_{ti}^D)\right) q_{ti}^D + 0.25 q_{ti}^B + \sum_{i=1}^{6} \ell_{ti} \tag{155}$$

$$= r_t(q_t^D)\, \frac{D V_t^D}{P_t} + 0.75\, \frac{B V_t^B}{\hat{P}_t} + \underbrace{\left(1 - r_t(q_t^D)\right) \sum_{i=1}^{6} q_{ti}^D + 0.25 \sum_{i=1}^{6} q_{ti}^B}_{\substack{\text{lost consumption due} \\ \text{to frictions}}} + \sum_{i=1}^{6} \ell_{ti} \tag{156}$$

$$= \underbrace{r_t(q_t^D)\, \frac{D V_t^D}{P_t} + 0.75\, \frac{B V_t^B}{\hat{P}_t}}_{\text{consumption after costs}} + \underbrace{\left(1 - r_t(q_t^D)\right) \frac{D V_t^D}{P_t} + 0.25\, \frac{B V_t^B}{\hat{P}_t}}_{\substack{\text{lost consumption due} \\ \text{to frictions}}} + \sum_{i=1}^{6} \ell_{ti} \tag{157}$$

$$\tag{158}$$

where we use that in a symmetric equilibrium, $r_t(q_t^D) = r_t(q_{ti}^D)$ is the same across agents, where we have defined the Dollar and Bitcoin velocity as before, as the share of Dollars respectively Bitcoins spent in each period, $V_t^D = \frac{\sum_{i=1}^{6} q_{ti}^D P_t}{D}$, and, $V_t^B = \frac{\sum_{i=1}^{6} q_{ti}^B \hat{P}_t}{B}$. In equilibrium, the number of unsold packages is zero, $\sum_{i=1}^{6} \ell_{ti} = 0$ for any t.

Sequential market clearing requires

$$0 = Y_t - Y_{t+1} = D \left(r_t(q_t^D)\, \frac{V_t^D}{P_t} - r_{t+1}(q_{t+1}^D)\, \frac{V_{t+1}^D}{P_{t+1}} \right) + 0.75\, B \left(\frac{V_t^B}{\hat{P}_t} - \frac{V_{t+1}^B}{\hat{P}_{t+1}} \right) \tag{159}$$

$$+ D \left(\left(1 - r_t(q_t^D)\right) \frac{V_t^D}{P_t} - (1 - r_{t+1})(q_{t+1}^D)\, \frac{V_{t+1}^D}{P_{t+1}} \right) + 0.25\, B \left(\frac{V_t^B}{\hat{P}_t} - \frac{V_{t+1}^B}{\hat{P}_{t+1}} \right) \tag{160}$$

$$= r_1(q_1^D)\, D \left(\frac{V_t^D}{P_t} - \frac{V_{t+1}^D}{P_{t+1}} \right) + 0.75\, B \left(\frac{V_t^B}{\hat{P}_t} - \frac{V_{t+1}^B}{\hat{P}_{t+1}} \right) \tag{161}$$

$$+ \left(1 - r_1(q_1^D)\right) D \left(\frac{V_t^D}{P_t} - \frac{V_{t+1}^D}{P_{t+1}} \right) + 0.25\, B \left(\frac{V_t^B}{\hat{P}_t} - \frac{V_{t+1}^B}{\hat{P}_{t+1}} \right) \tag{162}$$

where we have used that in a symmetric equilibrium, q_t^D is constant, since the transaction costs are reset in every period t. Therefore, $R(q_t^D) = R(q_1^D)$ and $r_t(q_t^D) = r_1(q_1^D)$ for all t. From above, in any equilibrium it holds

$$\hat{P}_{t+1} = \frac{0.75}{R(q_t^D)} P_{t+1}\, \frac{\hat{P}_t}{P_t} = \frac{0.75^t}{\prod_{k=1}^{t} R(q_k^D)} P_{t+1}\, \frac{\hat{P}_1}{P_1} = \left(\frac{0.75}{R(q_1^D)} \right)^t P_{t+1}\, \frac{\hat{P}_1}{P_1} \tag{163}$$

As before, a change in the Dollar price P_{t+1} uniquely determines the change in the Bitcoin price $\hat{P}_{t+1}$.

Replacing $\hat{P}_{t+1}$ in (190),

$$0 = Y_1 - Y_{t+1} = r_1(q_1^D)\, D\left(\frac{V_1^D}{P_1} - \frac{V_{t+1}^D}{P_{t+1}}\right) + 0.75\, B\left(\frac{V_1^B}{\hat{P}_1} - \frac{V_{t+1}^B}{\hat{P}_{t+1}}\right) \tag{164}$$

$$+ (1 - r_1(q_1^D))\, D\left(\frac{V_1^D}{P_1} - \frac{V_{t+1}^D}{P_{t+1}}\right) + 0.25\, B\left(\frac{V_1^B}{\hat{P}_1} - \frac{V_{t+1}^B}{\hat{P}_{t+1}}\right) \tag{165}$$

$$= r_1(q_1^D)\, D\left(\frac{V_1^D}{P_1} - \frac{V_{t+1}^D}{P_{t+1}}\right) + 0.75\, \frac{B}{\hat{P}_1}\left(V_1^B - \left(\frac{R(q_1^D)}{0.75}\right)^t \frac{V_{t+1}^B P_1}{P_{t+1}}\right) \tag{166}$$

$$\underbrace{+ (1 - r_1(q_1^D))\, D\left(\frac{V_1^D}{P_1} - \frac{V_{t+1}^D}{P_{t+1}}\right) + 0.25\, \frac{B}{\hat{P}_1}\left(V_1^B - \left(\frac{R(q_1^D)}{0.75}\right)^t \frac{V_{t+1}^B P_1}{P_{t+1}}\right)}_{\text{lost due to frictions}} \tag{167}$$

$$\tag{168}$$

A.1.4 Treatment: Monetary Policy and Transaction costs

We next introduce monetary policy in addition to transaction costs.

We analyze again green agent's optimization problem. A red agent's optimization is the same, with consumption shifted one time period ahead. Green agents are buyers and hence consume in even periods, and are sellers in odd periods. Let $\xi_t = 1$ when t is even, and zero when odd. The Lagrangian reads

$$L = \sum_{t=0}^{\infty} \xi_t \beta^t \Big[u(c_t) + \lambda_{13,t}(\hat{P}_t q_t^B) + \hat{\lambda}_{13,t}(b_t - \hat{P}_t q_t^B) \tag{169}$$

$$+ \lambda_{14,t}(P_t q_t^D) + \hat{\lambda}_{14,t}(d_t - P_t q_t^D) \tag{170}$$

$$+ \lambda_{15,t}(r_t(q_t^D)\, q_t^D + 0.75\, q_t^B - c_t) \tag{171}$$

$$+ \lambda_{16,t}(b_t - \hat{P}_t q_t^B - b_{t+1}) \tag{172}$$

$$+ \lambda_{17,t}(m(d_t - P_t q_t^D) - d_{t+1}) \Big] \tag{173}$$

$$+ (1 - \xi_t)\beta^t \Big[\lambda_{19,t}(y_t - x_t - z_t) \tag{174}$$

$$+ \lambda_{20,t}(b_t + \hat{P}_t x_t - b_{t+1}) \tag{175}$$

$$+ \lambda_{21,t}(m(d_t + P_t z_t) - d_{t+1}) \tag{176}$$

$$+ \lambda_{22,t} x_t + + \lambda_{23,t} z_t \Big] \tag{177}$$

If t is even and $t+1$ is odd,

$$
\begin{array}{lll}
I. & \frac{\partial L}{\partial c_t} & = u'(c_t) - \lambda_{15,t} = 0 \\
II. & \frac{\partial L}{\partial q_t^D} & = \lambda_{14,t} P_t - \hat{\lambda}_{14,t} P_t + R(q_t^D)\,\lambda_{15,t} - \lambda_{17,t}\, m\, P_t = 0 \\
III. & \frac{\partial L}{\partial q_t^B} & = \lambda_{13,t} \hat{P}_t - \hat{\lambda}_{13,t} \hat{P}_t + 0.75\,\lambda_{15,t} - \lambda_{16,t} \hat{P}_t = 0 \\
IV. & \frac{\partial L}{\partial x_{t+1}} & = -\lambda_{19,t+1} + \lambda_{20,t+1} \hat{P}_{t+1} + \lambda_{22,t+1} = 0 \\
V. & \frac{\partial L}{\partial z_{t+1}} & = -\lambda_{19,t+1} + \lambda_{21,t+1}\, m\, P_{t+1} + \lambda_{23,t+1} = 0 \\
VI. & \frac{\partial L}{\partial b_t} & = \hat{\lambda}_{13,t} \beta^t + \lambda_{16,t} \beta^t - \lambda_{20,t-1} \beta^{t-1} = 0 \\
VII. & \frac{\partial L}{\partial d_t} & = \hat{\lambda}_{14,t} \beta^t + \lambda_{17,t}\, m\, \beta^t - \lambda_{21,t-1} \beta^{t-1} = 0 \\
VIII. & \frac{\partial L}{\partial b_{t+1}} & = -\lambda_{16,t} \beta^t + \lambda_{20,t+1} \beta^{t+1} = 0 \\
IX. & \frac{\partial L}{\partial d_{t+1}} & = -\lambda_{17,t} \beta^t + \lambda_{21,t+1}\, m\, \beta^{t+1} = 0
\end{array}
\tag{178}
$$

As before, assuming that sellers sell some packages for both Bitcoins and Dollars in every period, i.e. $x_t > 0$ and $z_t > 0$ for all t, and that a buyer buys some packages using Bitcoin and Dollars in every period, $q_t^D, q_t^B > 0$, it holds $\lambda_{13,t} = \lambda_{14,t} = \lambda_{22,t} = \lambda_{23,t} = 0$. After solving for the Lagrange multipliers, the FOCs IV and V yield

$$
0.75\,\frac{P_{t+1}}{P_t} = m\, R(q_t^D)\,\frac{\hat{P}_{t+1}}{\hat{P}_t}. \tag{179}
$$

if the Dollar transaction cost increases (lower R), the Dollar inflation may stay constant if the Dollar multiplier m is increased by the "right" amount. Thus, for the Dollar inflation, an increase in the Dollar transaction cost can undo a rise in the Dollar multipler, or, Dollar transaction costs and the Dollar multiplier affect the Dollar inflation in opposite directions.

Writing this equilibrium condition in terms of the exchange rate, we obtain

$$
Q_{t+1} = m\,\frac{R(q_t^D)}{0.75}\,Q_t \tag{180}
$$

if the Dollar transaction cost increases (lower R), the Bitcoin exchange rate stays constant if the Dollar multipler is increased by the "right" amount. Thus, for the Bitcoin exchange rate, an increase in the Dollar transaction cost can undo a rise in the Dollar multipler, or, Dollar transaction costs and the Dollar multiplier affect the Bitcoin exchange rate in opposite directions. The initial exchange rate Q_0 remains undetermined. One obtains

$$
0 \leq \hat{\lambda}_{14,t} = \frac{1}{P_t} u'(c_t) R(q_t^D) - \beta^2 m^2 \frac{1}{P_{t+2}} u'(c_{t+2}) R(q_{t+2}^D) \tag{181}
$$

and

$$
0 \leq \hat{\lambda}_{13,t} = \frac{0.75}{\hat{P}_t} u'(c_t) - \beta^2 \frac{0.75}{\hat{P}_{t+2}} u'(c_{t+2}) \tag{182}
$$

If not all Bitcoins and Dollars are spent in every period, $\hat{P}_t q_t^B < b_t$ and $P_t q_t^D < d_t$,i.e. if there are savings, as we observe in the experiment, then $\hat{\lambda}_{13,t} = 0 = \hat{\lambda}_{14,t}$. In that case, FOC VIII and IX yield the consumption-Euler equations for consumption purchased in Bitcoins

$$
\frac{\hat{P}_{t+2}}{\hat{P}_t} = \beta^2 \frac{u'(c_{t+2})}{u'(c_t)}. \tag{183}
$$

Since the marginal Bitcoin transaction cost is contant in the number of packages purchased, it cancels

out and does not affect the pricing equation. For Dollars,

$$\frac{P_{t+2}}{P_t} = \beta^2 \, m^2 \, \frac{R(q^D_{t+2})}{R(q^D_t)} \, \frac{u'(c_{t+2})}{u'(c_t)}. \tag{184}$$

the transaction costs and the multiplier jointly affect the pricing equation.

Market clearing with transaction costs and monetary policy means that aggregate consumption is below the aggregate production, due to frictions and the Dollar supply grows by factor m per period. As before, let q^D_t the number of packages bought with Dollars, whereas $r_t(q^D_t)q^D_t$ is the consumption afforded with Dollars after accounting for transaction costs. Likewise, let q^B_t the number of packages bought with Bitcoins, whereas $0.75q^B_t$ is the consumption afforded with Bitcoins after accounting for transaction costs. We define the aggregate transaction costs as

$$\sum_{i=1}^{6} TraCo_{ti} = \sum_{i=1}^{6} (1 - r_t(q^D_{ti}))\, q^D_{ti} + 0.25 q^B_{ti} \tag{185}$$

In equilibrium, clearing of both goods markets requires

$$Y \equiv Y_t = 30 = \sum_{i=1}^{6} y_{ti} = \sum_{i=1}^{6} c_{ti} + \sum_{i=1}^{6} TraCo_{ti} + \sum_{i=1}^{6} \ell_{ti} \tag{186}$$

$$= \underbrace{r_t(q^D_t)\, \frac{D_t V^D_t}{P_t} + 0.75\, \frac{B V^B_t}{\hat{P}_t}}_{\text{consumption after costs}} + \underbrace{(1 - r_t(q^D_t))\, \frac{D_t V^D_t}{P_t} + 0.25\, \frac{B V^B_t}{\hat{P}_t}}_{\text{lost consumption due to frictions}} + \sum_{i=1}^{6} \ell_{ti} \tag{187}$$

$$= \underbrace{m\, r_t(q^D_t)\, \frac{D_{t-1} V^D_t}{P_t} + 0.75\, \frac{B V^B_t}{\hat{P}_t}}_{\text{consumption after costs}} + \underbrace{m\, (1 - r_t(q^D_t))\, \frac{D_{t-1} V^D_t}{P_t} + 0.25\, \frac{B V^B_t}{\hat{P}_t}}_{\text{lost consumption due to frictions}} + \sum_{i=1}^{6} \ell_{ti} \tag{188}$$

$$\tag{189}$$

Sequential market clearing requires

$$0 = Y_t - Y_{t+1} = D_t \left(r_t(q^D_t)\, \frac{V^D_t}{P_t} - m\, r_{t+1}(q^D_{t+1})\, \frac{V^D_{t+1}}{P_{t+1}} \right) + 0.75\, B \left(\frac{V^B_t}{\hat{P}_t} - \frac{V^B_{t+1}}{\hat{P}_{t+1}} \right) \tag{190}$$

$$+ D_t \left((1 - r_t(q^D_t))\, \frac{V^D_t}{P_t} - m\, (1 - r_{t+1})(q^D_{t+1})\, \frac{V^D_{t+1}}{P_{t+1}} \right) + 0.25\, B \left(\frac{V^B_t}{\hat{P}_t} - \frac{V^B_{t+1}}{\hat{P}_{t+1}} \right) \tag{191}$$

and

$$0 = Y_1 - Y_{t+1} = D_1 \left(r_1(q^D_1)\, \frac{V^D_1}{P_1} - m^t\, r_{t+1}(q^D_{t+1})\, \frac{V^D_{t+1}}{P_{t+1}} \right) + 0.75\, B \left(\frac{V^B_1}{\hat{P}_1} - \frac{V^B_{t+1}}{\hat{P}_{t+1}} \right) \tag{192}$$

$$+ D_1 \left((1 - r_1(q^D_1))\, \frac{V^D_1}{P_1} - m^t\, (1 - r_{t+1})(q^D_{t+1})\, \frac{V^D_{t+1}}{P_{t+1}} \right) + 0.25\, B \left(\frac{V^B_1}{\hat{P}_1} - \frac{V^B_{t+1}}{\hat{P}_{t+1}} \right) \tag{193}$$

A.2 Experimental instructions

Instructions

Welcome! Today you will be participating in an experiment studying economic decision-making. Your identity in this experiment will be **anonymized**, information on your decisions will only be linked to your station ID, and never connected to personally identifiable information. At the end of the experiment, you will be asked to provide your **IBAN** for payment. Your IBAN will not be stored: once we have processed your electronic payment, we will erase payment information. You may use a **calculator** anytime during the experiment.

There will be a set of instructions on the next page, please read these instructions carefully and **answer the four-question quiz** on the following page in order to proceed to the experiment. You can go back and forth between the instruction page and the quiz page as many times as necessary. Once all participants have answered all questions correctly, you will start the experiment. At the end of the experiment, you will be asked to fill out a **short questionnaire** and submit your IBAN.

Thank you for your participation and good luck!

Next

Instructions

Overview of the experiment

In this experiment, you will be trading with other players to get as many chips as you can by playing a real-time **market game** that uses a double auction mechanism (both buyers and sellers will be making offers). These chips determine your payout at the end of the experiment. To get chips, you will need to buy and sell packages of chips with other participants in the experiment. You will have to buy different types of packages of chips with different currencies. These market games are made up of a sequence of periods. Each sequence consists of **an indefinite number of periods**. Basically, how long it lasts is randomized. The number of periods played in each sequence is randomly determined in the following manner: At the end of each period, the computer will roll a virtual 6-sided dice. If the numbers 2, 3, 4, 5 or 6 are rolled from the dice, the sequence continues and you will continue playing the game, but if a '1' is rolled, the sequence ends and the game will restart. This means that all currency holdings and chips you currently have will disappear, and a new sequence will start. In other words, **after each period, the market game continues with a probability** 5/6 ≃ 83% **or ends with a probability** 1/6 ≃ 17%.

We will run **as many sequences as possible during the time for which you have been recruited**. After a sequence has ended, if there is not enough time remaining to start a new sequence, the experiment ends.

Before beginning the first sequence, you will have **2 practice periods** to familiarize yourself with the interface. Your decisions during those 2 practice periods will have no consequences on the actual experiment and will not count towards your earnings. It will be made clear to you and all other players when the actual experiment will start.

The market game

You are part of a group of **players** participating in markets where you buy and sell packages of chips. The rules are the same for all players. You will be split into equally sized groups of **buyers** and **sellers**. Each player will alternate between the roles of seller and buyer from period to period. Whether you start your first period as a seller or a buyer is randomly determined by the computer. For instance, if you are assigned the role of a buyer in period 1, you will then be a seller in period 2, then a buyer again in period 3, and so on until the sequence ends.

You will buy and sell chips in **two markets that each use different currencies**: Market A using Currency A and Market B using Currency B. Since you will alternate roles, buying chips is possible only every second period (when you are a buyer). Whenever you begin a period as a seller, you will be given 5 packages which you cannot use or keep for yourself, your goal as a seller is to sell these packages in order to increase your currency holdings to buy more packages when you are once again a buyer.

Number of chips per package

Chips are **bought and sold in packages**. Packages come in two types depending on which market you buy them from, the first type of package can only be bought from Market A which uses Currency A, the second type can only be bought from Market B which uses Currency B. When you buy a package, the number of chips you get depends on which currency/market you used to purchase the package and how many packages you already own.

- **Packages bought with currency A** can only be bought from Market A and will yield increasingly fewer chips, the more you purchase of these packages in a given period, the less each new package of this type will be worth to you. The first package bought using Currency A gives you 100 chips, the second package gives you 90 chips, ... , the 10th package only gives you 10 chips, ..., and any additional package beyond the 19th purchased only brings you one chip.

- **Packages bought with currency B** can only be bought from Market B and will always be worth 75 chips per package regardless of how many you have bought.

Package	1st	2nd	3rd	4th	5th	...	10th	11th	12nd	...	19th and beyond
Chip content (in A)	100	90	80	70	60	...	10	9	8	...	1
Chip content (in B)	75	75	75	75	75	...	75	75	75	...	75

Example: You buy 1 package using Currency A and 2 packages using Currency B in the first period of trading. Then you alternate roles to seller in the second period, then in the third period of trading, are a buyer again and you buy 2 more packages in Currency A and 1 more in package in Currency B. In total, you have purchased (100) + (100 + 90) = 290 chips using Currency A and 3 x 75 = 225 chips using Currency B, for a total of 290 + 225 = 515 chips so far.

What happens during a period of the market game

- When you **first start a sequence** as a buyer (which will last a random number of periods), you will receive 100 units of Currency A and 100 units of Currency B.
- At the beginning of **every period** when you are a seller, you will receive 5 packages, you must choose to allocate them to be sold on Market A or Market B.
- At the end of **every period** when you are a seller, you lose all packages you failed to sell.
- In each period, you will participate (either as a seller or as a buyer) in two different markets, one using Currency A (red boxes) and one using Currency B (blue boxes).
- Packages that yield diminishing numbers of chips are sold in Market A for Currency A, Packages that yield constant numbers of chips are sold in Market B for Currency B.
- You will carry over currency changes from period to period according to your actions as a buyer or seller.

Phases within a Period and their time limits

1. Allocating Packages Phase: Sellers' choose what allocation of their 5 packages goes to Market A or Market B (**30 seconds**).
2. Trading Phase: Buyers and Sellers make real-time offers for packages (**90 seconds**).

Note: A trading phase will close before time runs out whenever there are no more packages available for sale or there is no currency left to be spent. Hence, inncludig some waiting time, a period of the market game lasts a maximum of 3 minutes.

Allocating Packages Phase:

- This happens before the trading phase of a period
- Sellers are given 5 packages. They must choose how many of them they want to be offered on Market A and how many can be offered on Market B.

Trading Phase

- Sellers post **asks**, offers to sell a certain number of packages and the price they want to sell.
- Buyers post **bids**; offers to buy a number of packages and the highest price they will pay up to.
- Bids/asks can be changed at any time if they have not yet gone through.
- You can cancel your last bid/ask by clicking the "***Retract last bid***" button and "***Retract last ask***" button

Note: You can shortcut your participation in the market by clicking on the "***Accept best bid***" button as a seller (this means that you accept to sell at the highest price among all prices offered by the buyers), and by clicking the "***Accept best ask***" as a buyer (this means that you accept to buy at the lowest price among all prices offered

by the sellers).

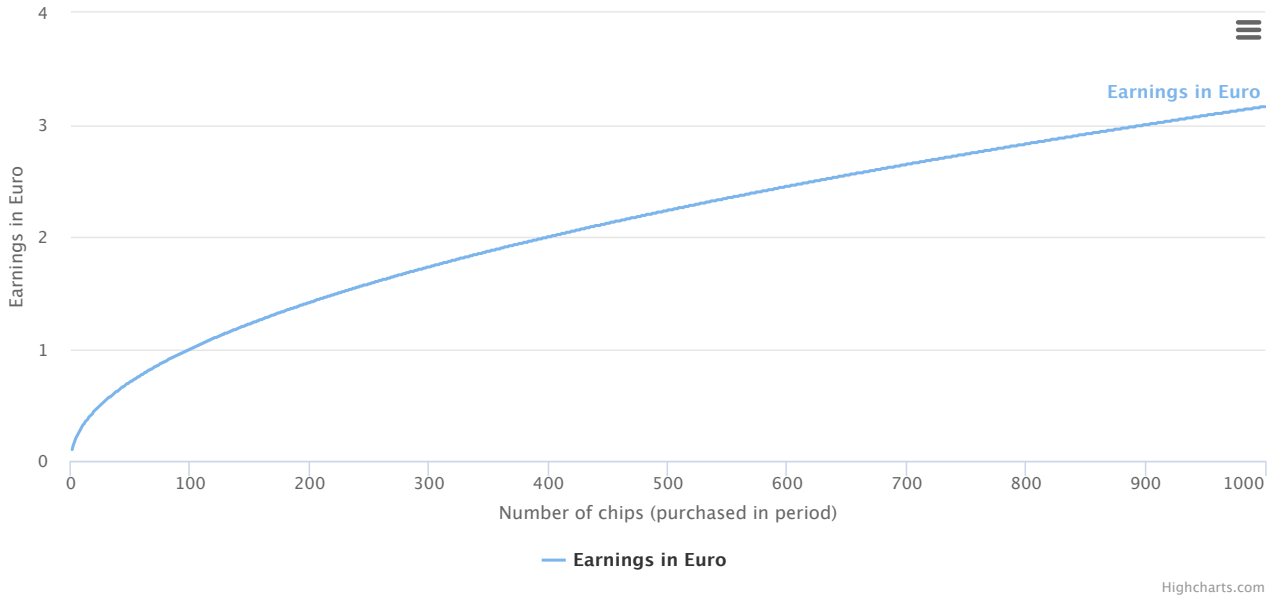
- A trade is finalized every time there is an ask price equal or less than a bid price.
  - The transaction price is the seller's asking price and the number of packages exchanged is the minimum between the number of packages offered by the seller, and desired by the buyer.
  - As a buyer, if no packages are for sale at or below your bid price, you will not buy any packages.
  - As a seller, if no packages are demanded for a price equal or higher to your ask price, you will not sell any packages.

  Example:You are a buyer and your bid is 2 packages at 100 units of Currency A. There is a seller whose ask is 3 packages at 80 units of Currency A. The transaction takes place and you buy from that seller 2 packages at 80 units of Currency A.

- You can submit as many asks and bids as you want as long as the markets are open.
  - As a buyer, you can never spend more currency than what you have allocated to each market. It can happen that you are not able to spend all your currency holdings. In this case, the remaining balance is then transferred to the next period.
  - As a seller, you can never sell more packages than you have allocated to a Market. It can happen that you are not able to sell all your packages. In this case, the unsold packages disappear at the end of that trading phase, which means that they may not be consumed or sold later.

Your earnings at the end of the experiment

The chips you purchase convert into money, hence you can accrue earnings only when you are a buyer. The payoff graphic below indicates how many Euros you can earn (y-axis) as a function of the number of chips you purchase in a given period (x-axis). There is also a slider that you can use to see the exact amount of Euros for each exact number of chips.



The more chips you buy, the more real-life money you can earn at the end of the experiment. However the chips you buy will convert into progressively less currency the more chips you accumulate within a single period.

Your total earnings in each sequence are the sum of your earnings in every period when you are a buyer during that sequence. At the end of the experiment, two sequences will be randomly selected (with equal probability out of all sequences played) and we will pay you **the money you earn during those two sequences, on top of a 9 euro participation compensation for your time and efforts**.

Summary

- You will play several sequences of a market game which lasts a randomized number of periods. After each period, the game ends with a 1/6 ≃ 17% probability. When this happens, all currency holdings are reset to zero and a new sequence starts.
- You will play as many sequences as time allows us. During each sequence, you will play alternating between being buyers and sellers of packages of chips. You can buy and sell chips in Market A using Currency A, or Market B using Currency B.
- At the beginning of each period, when you are a seller, you receive 5 packages of chips to sell to choose to allocate to Market A or Market B, these packages cannot be used or kept by you after each period.
- You start every sequence with 100 units of Currency A and 100 of Currency B. Your changes will carry over from period to period.
- The more packages you buy in Currency A, the fewer chips each additional package contains. Packages bought in Currency B always contain the same amount of chips. This resets every period.
- The more chips you purchase in each period, the higher your payoff but earnings do not increase as fast as the number of chips purchased. Only the total earnings from two sequences plus 9 euros will be paid out to you at the end of the experiment.

Next

Quiz

Instruction

1. Imagine that in a given period, you purchase 3 packages in currency A and 1 in currency B.

(a) How many chips did you purchase?

(b) How many Euros did you make? (Please keep two decimal points)

2. Imagine that you are a seller and your ask is 3 packages at 10 units of currency A. There is a buyer whose bid is 2 packages at 18 units of currency A. Which one of the following applies?

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3. which one of the following applies?

Next

A.3 Graphical user interfaces (GUI)

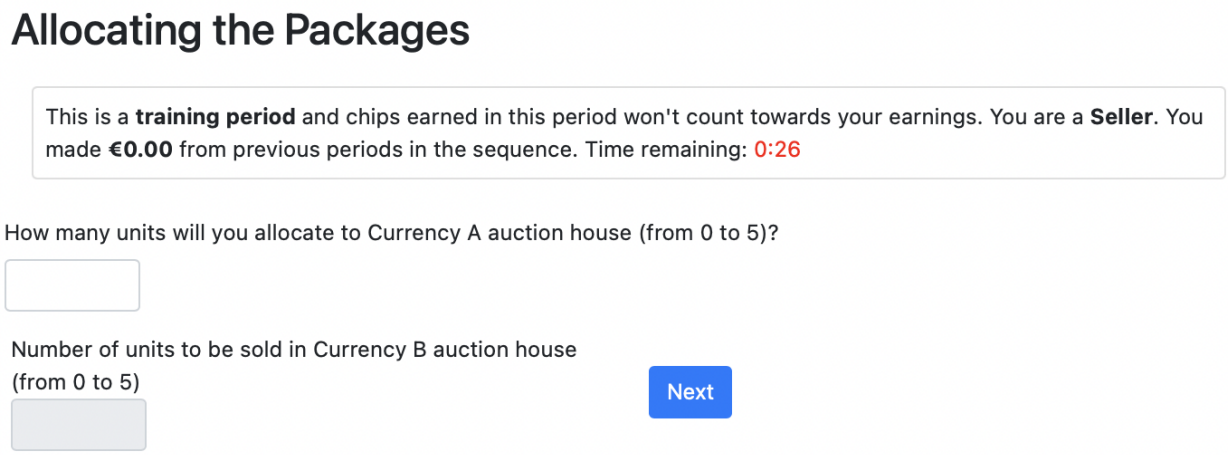


Figure 6: Screen of the sellers' allocation page of packages between the two markets

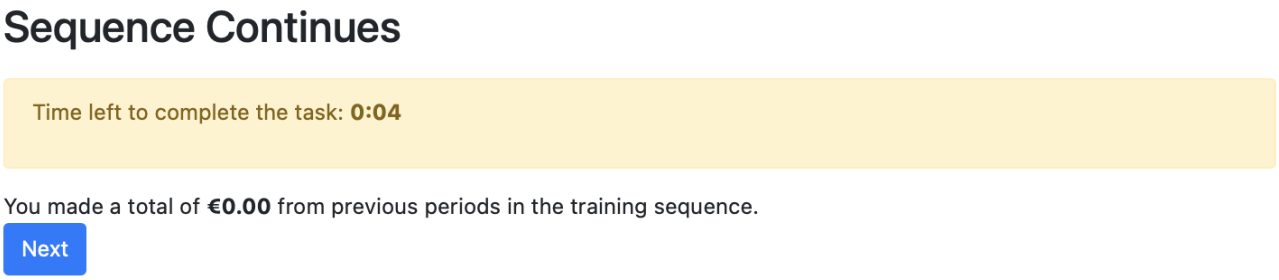


Figure 7: Screen indicating a continuing sequence