

Leverage and Asset Prices: An Experiment.

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Abstract

We test the asset pricing implications of leverage (collateralized borrowing) in the laboratory. To this purpose, we develop a model of leverage amenable to laboratory implementation and gather experimental data. In the laboratory, assets that can be used as collateral fetch higher prices than assets that cannot, even though assets' payoffs are identical in all states of nature. Hence, collateral value creates deviations from the Law of One Price. The spread between collateralizable and non-collateralizable assets is significant and quantitatively close to theoretical predictions. Finally, also as theory suggests, with leverage gains from trade are realized to a greater extent.

Keywords: Leverage, Asset Pricing, Collateral Value, Law of One Price, Experimental Economics.

JEL Codes: A10, C90, G12.

1 Introduction

The 2008 financial crisis highlighted the impact that leverage has on financial system stability. The crisis was preceded by a sharp increase of leverage in the financial system, both at the institution and at the asset level. The crisis poster-children,

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AIG and Lehman, as well as the systemic banking troubles in the US and Europe illustrate the risks that margin calls pose for the financial system’s liquidity and solvency. Whereas before the crisis, the financial literature explained asset price fluctuations and their effect on the economy by focusing mainly on fundamentals (such as the interest rate, or future cash flows), after the crisis, the emphasis shifted toward understanding the implications of leverage.¹

During the crisis, it also became apparent that cross-sectional differences in asset prices were related to heterogeneity in asset collateral capacities. Several papers have studied the cross-sectional implications of collateralized borrowing in a world where agents are heterogeneous and markets incomplete: e.g., Fostel and Geanakoplos (2008) in a collateral general equilibrium model, Garleanu and Pedersen (2011) in a CAPM model, and Brumm et al. (2016) in an infinite-horizon exchange economy. These papers show that collateral value increases asset prices, creating deviations from the Law of One Price.²

Leverage affects asset prices because when assets can be used as collateral, their prices not only reflect future cash flows, but also their efficiency as liquidity providers. Fostel and Geanakoplos (2008) show that the price of any asset can be decomposed into two parts: its payoff value and its collateral value. The payoff value reflects the asset owner’s valuation of the future stream of payments, i.e., it is the value attached to the asset due to its investment role. The collateral value reflects the asset owner’s valuation of being able to use the asset as collateral to borrow. The asset collateral role is priced in equilibrium and, as a result, creates deviations from the Law of One Price: two assets with identical payoffs are priced differently if their collateral capacities are different.³ A well documented example of such deviations is the so-called “CDS-basis”—that is, the price difference between Treasuries and covered CDS position— which became more severe during the recent crisis. Economic theory also predicts that leverage allows gains from trade to be realized to a greater extent.

¹See for instance, Acharya and Viswanathan (2011), Adrian and Shin (2010), Brunnermeier and Pedersen (2009), Fostel and Geanakoplos (2008, 2012a, 2012b, 2014, 2015), Garleanu and Pedersen (2011), Geanakoplos (2010), Simsek (2013). Early studies on the effect of leverage on asset prices were published before the crisis—see, for instance, Hindy (1994) in a partial equilibrium model, and Geanakoplos (1997 and 2003) in a general equilibrium model with incomplete markets.

²Other drivers of deviations from the Law of One Price, similar to collateral, are the “divertibility premium” under incentive problems in Biais, Hombert, and Weill (2016); or the “liquidity premium” in new monetarist papers such as Lagos (2010), Li, Rochetau, and Weill (2012) and Lester, Postelwaite, and Wright (2012).

³An early example of collateral value generating deviation from the Law of One Price can be found in Geanakoplos (2003).

When agents borrow using the assets as collateral, trading activity increases and the asset is held in equilibrium by those who value it the most.

In this paper, we study a leverage economy in a laboratory financial market. To this purpose, we build a model of a financial economy with incomplete markets, heterogeneous agents, and collateralized borrowing that is amenable to laboratory implementation. Agents trade two risky assets with identical payoffs in all states of the world. Only one of the two assets can be used as collateral. In equilibrium, the price of the collateralizable asset is higher than that of the asset that cannot be used as collateral; since the two assets have identical payoffs, this spread represents a deviation from the Law of One Price due to the presence of collateral value. Additionally, in equilibrium, gains from trade are fully realized for the collateralizable asset, but only partially for the non collateralizable one.

An experimental approach is appropriate to study the effect of leverage on financial markets for two reasons. First, it allows us to study the interplay between subjects' behavior in the laboratory and the theoretical effect of leverage on asset prices. Second, in the laboratory, we can create markets where assets have the exact same payoff, but different collateral capacity.⁴

The laboratory results confirm the theory's main predictions. First, and most importantly, the price of the asset that can be used as collateral is higher than that of the asset that cannot. The spread between the two assets is significant and quantitatively very close to what theory predicts. In other words, subjects in the laboratory are willing to pay more for the asset that can be used as collateral despite the two assets having identical payoffs in all states of the world; that is, collateral value creates a deviation from the Law of One Price in the laboratory. Second, as theory suggests, leverage allows gains from trade to be realized to a greater extent in the laboratory: the asset that can be used as collateral is allocated more efficiently than the asset that cannot. Subjects' trading behaviors in terms of borrowing and final allocation are relatively stable throughout the experiment. However, the spread between the prices of the collateralizable and the non-collateralizable increases gradually as the experiment proceeds, converging toward the theoretical equilibrium prediction; that is, subjects discover the value of collateral as they trade. Finally, the spread observed in the laboratory between the prices of the two assets seems to arise for the same reason highlighted by the theory: in the laboratory, subjects are willing to

⁴This is very hard to do with field data; for instance, even when comparing Treasuries to covered CDS positions, counterparty risk muddles the water.

pay a positive price for an extra unit of collateral because they are borrowing (and cash) constrained; the collateralizable asset allows them to borrow and increase their holdings of risky assets.

Our paper is related to a large and important literature in experimental finance, starting from Smith (1962), which tests asset pricing models in a controlled laboratory environment where subjects trade in a double auction. For instance, King et al. (1988) first tested the effect of leverage on asset prices and found that leverage increases the frequency and the intensity of bubbles. More recently, the effect of leverage on asset price bubbles in a double auction market has been studied by Fullbrun and Neugebauer (2012). In this experimental literature, the effect of leverage is similar, from an experimental standpoint, to that of an increase in cash endowments: see Caginalp et al. (1998), and Caginalp et al. (2001).⁵

It is important to remark that our approach differs from this literature in two ways. First, we allow subjects to trade more than one asset, with different collateral capacities, in the same market. As a result, any spread between asset prices observed in the laboratory cannot be explained by a change in subjects' budget sets or available liquidity: agents solve a portfolio problem subject to the one budget set that simultaneously limits their ability to purchase both assets. Yet, in the laboratory, consistent with the theory, the price of the asset that can be used as collateral is higher than that of the asset that cannot, despite identical payoffs in all states of the world. This is a new experimental result that is neither implied nor a consequence of the findings in the experimental literature on the effect of relaxation of the budget constraints on asset prices. Our novel result shows that the collateral constraints that generate deviations from the Law of One Price are robust theoretical findings.

Second, most of these experimental papers on bubbles were run before the relevance of leverage was theoretically understood—indeed King et al. (1993) conjectures that leverage should dampen bubbles. In all the experimental work—including that conducted after the crisis, such as Fullbrun and Neugebauer (2012)—the experiment is designed without embedding the theoretical mechanisms through which leverage affects asset prices. As a result, in the financial economy implemented in the laboratory, the effect of liquidity or leverage on asset prices is not an equilibrium outcome;

⁵Our work is also related to that of Haruvy and Noussair (2006), who find that short sale constraints—a financial technology achieving the opposite effect of leverage—attenuates bubbles in the laboratory. For a summary of the experimental literature on bubbles, see Porter and Smith (2003).

instead, it occurs because of subjects' behavioral biases. Indeed, the formation of bubbles is generally interpreted as arising from lack of common expectations among subjects (although the rules of the game are common knowledge) and the resulting uncertainty over the behavior of others (see Porter and Smith, 2003, and Smith et al. 1988 and Cheung et al. 2014). Because of this, bubbles are dampened and sometimes altogether disappear with experienced subjects (King et al., 1988; Smith et al. 1988; Dufwenberg et al. 2005; Fullbrun and Neugebauer, 2012; and Akiyama, 2014) or when the asset market is framed more intuitively (Kirchler et al., 2012 and Huber and Kirchler 2012). In contrast, in our paper, we study a different environment in which, due to market incompleteness, agents' heterogeneity, and collateralized borrowing, theory predicts that prices should increase if subjects are able to leverage; experimentally, the data confirm that leverage does in fact increase asset prices. Therefore, whereas the literature on bubbles highlights possible effects of leverage in economies where such effects theoretically should not exist, our experimental results confirm the importance of leverage in markets where theory predicts that leverage should have a role.⁶

The paper is organized as follows. Section 2 develops the theoretical model. Section 3 describes the experiment design and the experimental procedures. Section 4 presents the results. Section 5 concludes. All supplementary material is presented in the Appendix.

2 Theory

2.1 The Model

We develop a model of (security-based) leverage and asset prices that is amenable to laboratory implementation. Our model retains the main features of models in the theoretical literature (e.g., Fostel and Geanakoplos, 2008): market incompleteness, agent heterogeneity, and collateral as a repayment enforcement mechanism. In the economy, two risky assets are traded, but only one of them can be used as collateral to borrow money. A spread between the prices of the collateralizable and the non-collateralizable asset arises in equilibrium due to the presence of collateral value.

⁶Indeed, in our experiment, subjects discover the (theoretical) value of the collateral (and therefore the spreads between collateralizable and non collateralizable assets increases) as they trade through the rounds of the experiment.

Time and Assets

We consider a two-period economy, with time $t = 0, 1$. At time 1, there are two states of the nature, $s = High$ and $s = Low$, which occur with probability q and $1 - q$. There is a continuum of agents of two different types, indexed by $i = B, S$, denoting Buyers and Sellers. Each type has mass one.

There are three assets in the economy, cash and two risky assets, Y and Z , with payoffs in units of cash. Both risky assets have identical payoffs in both states of the world.

In state *Low*, they both pay D_{Low} . In state *High*, Buyers value the assets more than Sellers do, that is, $D_{High}^B > D_{High}^S$.

Nevertheless, for each type i , $D_{High}^i > D_{Low}$, that is, the payoff in the high state of the world is always higher than the payoff in the low state of the world.⁷ The difference in payoffs may be interpreted as Buyers and Sellers owning different technologies that affect the asset's productivity. As in the theoretical literature, the presence of agents' heterogeneity is crucial for leverage to have an effect on trading activity and asset pricing. We model heterogeneity through heterogeneous asset valuations since it makes the experimental implementation simpler.⁸

Finally, we denote the price of the risky assets Y and Z in terms of cash as p_Y and p_Z respectively.

Assets and Collateral

Although the risky assets Y and Z have identical payoffs only one of them, Y , can be pledged as collateral to borrow money.⁹

More precisely, we assume that agents can borrow from a financial institution (a bank) only on secured terms by posting the asset Y as collateral.¹⁰ Furthermore, we

⁷This is similar to the way gains from trade arise in the double auction literature, see, e.g., Smith (1962), Plott and Sunder (1982), and subsequent papers.

⁸In Fostel and Geanakoplos (2008), heterogeneity is modeled as differences in subjective probabilities over the states of the world. In Garleanu and Pedersen (2011), heterogeneity is modeled as differences in risk aversion. Differences in subjective probabilities, heterogeneous asset valuation, risk aversion, and wealth distribution all create the same effect of leverage on asset prices due to collateral values; for a detailed discussion see Fostel and Geanakoplos (2014).

⁹A real world example of this is the so-called CDS-basis, widely discussed in the empirical finance literature.

¹⁰The focus of our paper is to study the effect of leverage on asset prices in the laboratory. To

assume that the maximum amount agents can borrow per unit of Y is the asset payoff in state Low , D_{Low} . This collateral constraint is sometimes referred to as Value at Risk equal to zero ($VaR = 0$) and is widely used in the literature.¹¹ Since the bank can recoup its loan in both states of the world by selling the collateral, it will charge the risk-free rate, which we assume without loss of generality to be zero. Hence, the amount borrowed at time 0, is also the amount to be repaid at time 1.¹²

In other words, while Z can only be bought with cash (by paying p_Z at the time of the purchase), Y can be bought on margin (by buying the asset and using it as collateral to borrow money at the time of the purchase). Given the collateral constraint above, the minimum downpayment to purchase one unit of asset Y is $p_Y - D_{Low}$, the total value of the asset minus the maximum amount that can be borrowed using the asset as collateral.

Agents' Problem and Equilibrium

At $t = 0$, agents of type $i = B, S$ have an endowment of m^i units of cash and of a_Y^i and a_Z^i units of the risky assets. Agent i has a CRRA payoff function for state $s = High, Low$, given by:

$$u^i(x_s) = \begin{cases} \frac{x_s^{\beta_i}}{\beta_i}, & \beta_i \neq 0, \\ \log(x_s), & \beta_i = 0, \end{cases} \quad (1)$$

where $x_s = w + D_s^i y + D_s^i z - \varphi$. In the last expression w denotes final cash holdings, y and z refer to final asset holdings, $D_s^i y$ and $D_s^i z$ denote the dividends accruing from assets holdings in state s , and φ is total debt repayment. Agents' attitude toward risk is parameterized by β_i : if $\beta_i = 1$, agent i is risk neutral; if $\beta_i > 1$, agent i is risk loving; and if $\beta_i < 1$, agent i is risk averse.

The expected payoff to an agent of type i is given by

$$U^i = qu^i(x_{High}) + (1 - q)u^i(x_{Low}). \quad (2)$$

make the implementation simple, we have subjects trade in two markets only, the markets of the risky assets Y and Z , and we let them borrow from the experimenter (the bank).

¹¹See for instance, Acharya and Viswanathan (2011), Adrian and Shin (2010), Brunnermeier and Pedersen (2009), Fostel and Geanakoplos (2008, 2015), Garleanu and Pedersen (2011).

¹²These assumptions are only made to make the laboratory implementation simple; if we relaxed the collateral constraint or if we assumed that the riskless interest rate is positive, leverage would still increase asset prices (see, e.g., Fostel and Geanakoplos, 2012a, and Simsek, 2013).

Agents take asset prices p_Y and p_Z as given and choose asset holdings y and z , cash holdings w , and borrowing φ in order to maximize (2) subject to the budget constraint (3) and the collateral constraint (4):

$$w + p_Y y + p_Z z \leq m^i + p_Y a_Y^i + p_Z a_Z^i + \varphi \quad (3)$$

$$\varphi \leq D_{Low} y. \quad (4)$$

Finally a collateral equilibrium is given by asset prices p_Y and p_Z , cash holdings w , asset holdings y and z , and borrowing φ at $t = 0$ such that asset markets clear and that agents maximize their payoff function (2) subject to constraints (3) and (4).

2.2 Equilibrium Analysis

In order to study the asset pricing implication of collateralized borrowing, we solve for equilibrium in the model for the parameter values reported in Table 1.

Table 1: Parameter Values.

<i>Parameters</i>	D_{Low}	D_{High}^B	D_{High}^S	q	m^B	m^S	a_Y^B	a_Z^B	a_Y^S	a_Z^S
<i>Values</i>	100	750	250	0.8	400	0	0	0	1	2

This table shows the parameter values used for the equilibrium calculation.

Under this parametrization, the assets' payoff in state Low is $D_{Low} = 100$; in state High is $D_{High}^B = 750$ for Buyers and $D_{High}^S = 250$ for Sellers. The probability of state High is $q = 0.8$. Buyers have initial cash endowments $m^B = 400$, whereas Sellers have no cash. Sellers have initial asset endowments, $a_Y^S = 1$ and $a_Z^S = 2$, whereas Buyers have no asset endowment. Note that since Buyers have all the cash endowment and Sellers have all the asset endowment, Buyers are on the demand side and Sellers on the supply side of the asset market.¹³

In order to gain intuition on how the equilibrium works, Table 2 first presents the equilibrium values in the risk neutral case, $\beta_i = \beta = 1$.¹⁴

¹³We discuss in detail our choice of parameter values in Appendix II.

¹⁴See Appendix I for a discussion on how to solve for the equilibrium and for the proof that the equilibrium is unique.

Table 2: Equilibrium in the Risk Neutral Case ($\beta = 1$)

Asset Prices		
p_Y	285	
p_Z	220	
	Spread: 65	
Allocations and Payoffs		
	Buyers	Sellers
y	1	0
z	0.98	1.02
φ	100	0
w	0	400

This table shows the equilibrium under the assumption that all subjects are risk neutral.

The first thing to notice is that the price of asset Y is higher than that of asset Z : $p_Y = 285 > 220 = p_Z$. That is, the asset that can be used as collateral fetches a higher price. Since both assets pay identical payoffs in all states of the world, this equilibrium pricing is a deviation from the Law of One Price.

Individual decisions are described in the lower part of Table 2.¹⁵ In equilibrium, the Buyers use all their cash endowments and borrowing capacity to buy all the assets they can afford. This happens because their expected value of both risky assets ($0.8(750) + 0.2(100) = 620$) is higher than their prices in equilibrium, and the solution to their optimization problem is a corner solution. As a consequence, they buy Y on margin and Z with cash. They borrow the maximum they can using 1 unit of Y as collateral, 100, and use all their cash endowment of 400 to pay for the downpayment of 1 unit of Y and .98 units of Z . Buyers are indifferent between using one extra unit of cash to buy an extra unit of Z or as a downpayment to buy an extra unit of Y on margin because the expected returns of these two investments are the same (see Appendix I).

In contrast, the solution to the Sellers' optimization problem is not a corner solution: at a price of 220 they are indifferent between holding cash and holding Z , as their expected value ($0.8(250) + 0.2(100)$) equals the price of Z . However, they sell all their endowment of Y given that their expected value is lower than the price of 285.

In equilibrium, assets change hands from Sellers (who value the assets less) to Buyers (who value the assets more), thereby realizing some of the gains from trade in the

¹⁵In the experiment, the assets are not perfectly divisible; hence, we will use as a theoretical benchmark the closest integer approximation.

economy. Buyers end up holding all the supply of Y and share the supply of Z with Sellers.

The case with Risk Aversion

The most salient feature of the equilibrium described above, is the deviation from the Law of One Price. Of course, this deviation does not hinge on agents' risk neutrality. Table 3 presents the equilibrium for different values of risk aversion.¹⁶

Table 3: Equilibrium for different levels of β .

β	-0.25	0.00	0.25	0.50	0.75	1.00	1.25	1.50
	Risk-Averse					Risk Neutral	Risk-Loving	
p_Y	213	231	252	268	278	285	289	292
p_Z	213	215	216	217	219	220	221	223
Spread	0	16	36	51	59	65	68	69
y^B	1	1	1	1	1	1	1	1
z^B	1.2	1.24	1.14	1.06	1.01	.97	.96	.94
φ	69	100	100	100	100	100	100	100
w	0	0	0	0	0	0	0	0

This table shows the equilibrium for different β .

There is a positive spread between asset prices even for very high levels of risk aversion. When there is a positive spread, subjects' behavior in equilibrium is as the one described above for the risk-neutral case: Buyers borrow the maximum, hold no cash at the end of the round, buy all the supply of Y on margin, and share asset Z with Sellers.

Note that the spread in prices is decreasing in the level of risk aversion. For extreme values of risk aversion ($\beta = -.25$), the spread disappears. The reason for this is that, for extreme levels of risk aversion, Buyers are less willing to hold risky assets and hence the collateral constraint becomes not binding. Since the two assets pay the same in all states of the world, and Buyers do not value the collateral role of Y , the two assets fetch the same price in equilibrium. It turns out that, for values of β greater than $\beta = -0.16$, Buyers' collateral constraint is binding and a deviation from Law of One Price (a spread between the prices of Y and Z) arises in equilibrium.

Leverage, Collateral Value, and Law of One Price

In our model, the equilibrium prices of two assets with identical payoffs in all states

¹⁶See Appendix I for a discussion on how solve for the equilibrium for the different values of β in Table 3, as well as for a discussion on uniqueness.

of the world are different. That is, the Law of One Price does not hold.

Fostel and Geanakoplos (2008) show that this happens because in an economy with collateralized borrowing, assets have a dual role: they are not only investment opportunities (i.e., they give a right to a future cash flow), but also allow investors to borrow money. When collateral constraints are binding, deviations from the Law of One Price arise due to collateral value. Collateral value is also what generates the spread between the prices of Y and Z in our model: agents are willing to pay more for the asset that can be used as collateral (Y).¹⁷

3 The Experiment

3.1 The Experiment Design

The experiment was run at the Interdisciplinary Center for Economic Science, ICES, at George Mason University. We recruited subjects in all disciplines at George Mason University using the ICES online recruiting system.¹⁸ Subjects had no previous experience with the experiment. The experiment was programmed and conducted with the software *z-Tree*.¹⁹

The experiment consisted of seven sessions. In Session 3, 16 students participated and in all the other sessions, 12 students participated, for a total of 88 students.

In each session, we implemented the economy described in Table 1 of Section 2.2. Each session consisted of three parts: Part I, Part II, and Part III. In each part of the experiment, subjects traded among each other in a double auction. However, in the first two parts, subjects played a simplified version of the economy. In Part I, the supply of Y was set to zero and the supply of cash was set to 300; that is, students traded in a one-asset economy. In Part II, students traded both assets, but could not use asset Y to borrow money.

¹⁷Fostel and Geanakoplos (2008) provide a general decomposition of the price of a collateralizable asset into *Payoff Value* (the present discounted value of the expected marginal utility of holding asset) and *Collateral Value* (the amount agents are willing to pay for the asset collateral capacity). One can show that, in our model, the spread between the prices of assets Y and Z equals the *Collateral Value* as defined in Fostel and Geanakoplos (2008).

¹⁸When the number of students willing to participate was larger than the number needed, we chose the subjects randomly in order to reduce the chance that the students in the experiment knew each other.

¹⁹See Fischbacher (2007).

In each session, we ran several rounds of the same economy: two rounds in Part I, four rounds in Part II, and 14 rounds in Part III. Parts I, II, and the first 4 rounds of Part III were for practice only. Only the last 10 rounds of Part III were used to pay the students.

We now describe Part III; the procedures for Part I and II are analogous.²⁰

3.2 The Procedures

1. At the beginning of the experiment, subjects read the experimental instructions on their computer screens. As part of the online instructions, students were asked to answer questions about the experiment and were not allowed to move forward until they answered correctly. At any time, subjects could ask questions to the experimenters, which were answered in private. Students were also given a “reference sheet” with a summary of the experimental procedures that they could consult during the experiment.²¹
2. All payoffs were denominated in an experimental currency called $E\$$. In the laboratory, the risky assets were referred to as “widgets;” asset Z was called a CIRCLE widget and asset Y a SQUARE widget.
3. At the beginning of the session, each subject was randomly assigned to be either a Buyer or a Seller. Half of the subjects were Buyers and half were Sellers. Subjects could see their role in the left corner of their computer. Subjects maintained the same role throughout the experiment.
4. At the beginning of the round, each Buyer was given the endowment of $E\$400$ and each Seller was given the endowment of two units of asset Z and one unit of asset Y .
5. Subjects traded the two assets by exchanging them among themselves for 160 seconds. They used the trading platform shown in Appendix X.
6. During the 160 seconds of trading activity, Buyers could post Buy Offers and Sellers could post Sell Offers for either asset. Each offer was for a single unit of each asset.

²⁰Appendix X presents instructions and screenshots for each part of the experiment.

²¹Appendix X includes the “reference sheets” distributed to subjects.

7. To post a Sell Offer, a Seller would enter the price that (s)he was willing to receive. The offer appeared immediately on everyone’s screen, in a separate table for each market. The identity of the subject making the offer was not revealed.
8. To post a Buy Offer for asset Z , a Buyer would enter the price (s)he was willing to pay, and the offer would appear in a table. To post a Buy Offer for asset Y , a Buyer would not only enter the price (s)he was willing to pay, but also the Borrowing (s)he wanted to obtain from the Bank using the asset as collateral.²² In the experiment, Borrowing was referred to as “Cash Transfer” and the role of the Bank was played by the experimenters. Buyers and Sellers could cancel their offers at any time.
9. A trade occurred if the best Sell Offer was lower or equal to the best Buy Offer. This situation was recognized by the system, and the trade took place automatically.
10. After the 160 seconds elapsed, the state of the world was realized.²³ Then, subjects’ payoffs were computed and appeared on subjects’ screens. The payoff for the round was calculated as the sum of final cash holdings and payoffs accruing from asset holdings, minus (in the case of Buyers) any debt repayment.
11. After round one ended, a new round started. The experiment continued until all 14 were played. Each round was independent from the previous one: subjects were not allowed to carry over cash or assets from one round to the next.

At the end of the experiment, we randomly chose one round out of the last 10 rounds of Part III for payment purposes. The payoff of that round was converted into cash at the rate of E\$30 per \$1. In the double-auction part of the experiment, subjects were paid on average \$31.

After Part III, we elicited subjects’ risk aversion using the Holt and Laury (2002) procedure (see Appendix III for a description of the procedure). Subjects were paid on average \$3 in the elicitation phase of the experiment.

²²A Seller could submit any number of Sell Offers as long as (s)he had assets left to sell. A Buyer could submit any number of Buy Offers as long as the downpayment was smaller than the cash available to the Buyer.

²³The state of the world each period was randomized subject to the constraint that eight High rounds occurred. This ensured that the ex-post return from leverage remained similar across sessions.

We paid subjects in private immediately after the end of the experiment. The experimental sessions lasted approximately two and a half hours.

4 Results

4.1 The Theoretical Benchmark

In analyzing our empirical results, we compare subjects' choices in the laboratory with the prediction of the theoretical model in Section 2. To do that, we need to take a stand on the level of risk aversion in the laboratory. We do so by eliciting subjects' risk aversion through the Holt and Laury procedure (2002) at the end of the double auction. In the Holt and Laury procedure, each subject makes ten binary choices between two lotteries, one safer and one riskier; assuming subjects have a CRRA utility function—the same utility function as in our theoretical model—Holt and Laury map the number of safer choices a subject makes in the laboratory to an interval for a subject's risk aversion parameter β (see Table III.2 in Appendix III).

In the laboratory, across all subjects of all sessions, the median number of safer choices in the laboratory is 5 (see Appendix III, Table III.3 for a set of descriptive statistics on subjects' elicited risk aversion). This implies an interval (0.59, 0.85) for subjects' median risk aversion parameter β , with a middle point of $\beta = 0.72$; Holt and Laury (2002) refer to such a level of risk aversion as “Slightly Risk Averse.” Finally, we do not observe meaningful variation in subjects' risk aversion between Buyers and Sellers (see Appendix III, Table III.4 for the results of non-parametric tests on subjects' elicited risk aversion).

Table 4: Theoretical Benchmark

β	0.59	0.72	0.85
Asset Prices			
p_Y	272	277	281
p_Z	217	218	219
Spread	55	59	62
Allocations			
y^B	1	1	1
z^B	1	1	1
φ	100	100	100
w^B	0	0	0

This table shows the equilibrium prices and holdings at the low (0.59), middle (0.72), and high (0.85) risk-aversion coefficients suggested by the subjects' median response to the Holt and Laury (2002) procedure.

Table 4 presents the theoretical equilibria at the boundaries and at the middle point of the risk aversion interval for the median subject.²⁴ The equilibria are very similar; for this reason, when we compare the laboratory results with the theoretical outcomes, we will just use as our theoretical benchmark the theoretical prediction for the middle point of the interval, that is, $\beta = .72$.²⁵

Compared to the risk-neutral case described in Section 2, the prices of both (risky) assets Y and Z are slightly lower (277 and 218, versus 285 and 220 in the risk-neutral case), reflecting subjects' aversion to risk. The spread between the prices of the two assets is slightly smaller (59 vs 65). The lower spread stems from the fact that collateralized borrowing is now slightly less valuable, since risk-averse Buyers are less eager to obtain the risky assets. Finally, as in the risk-neutral case, Buyers borrow the maximum ($\varphi = 100$) and use all their cash endowment to buy the risky assets ($w^B = 0$). Also, as in the risk-neutral case, Buyers use their purchasing power to buy all the supply of asset Y ($y^B = 1$) and half of the supply of asset Z ($z^B = 1$).

4.2 Asset Prices and Deviation from the Law of One Price

The laboratory results confirm the main prediction of the theory: although Y and Z have identical payoffs in all states of nature, the price of the collateralizable asset

²⁴Asset final holdings have been rounded to the nearest unit to reflect the fact that assets are indivisible in the laboratory. The theoretical equilibrium Buyers' holdings of asset Z are 1.04, 1.02, and 0.99.

²⁵The equilibrium is discussed in detail in Appendix I.

Y is greater than that of Z . That is, there are deviations from the Law of One Price due to the presence of Collateral Value.

Table 5: Average Asset Prices

	All Sessions	S1	S2	S3	S4	S5	S6	S7
Y	268 (21)	240 (14)	262 (8)	276 (15)	261 (3)	258 (16)	296 (6)	277 (22)
Z	224 (20)	217 (11)	246 (3)	223 (12)	244 (4)	210 (24)	205 (8)	234 (12)
Spread	45	24	16	54	18	47	92	43

This table shows the mean and standard deviation (in parentheses), computed across the last ten rounds of Part III, of the transaction prices of assets Y and Z and the spread between them.

Table 5 shows the average prices of the two assets across all transactions, rounds, and sessions.²⁶ The average trade price of Y is 268 whereas that of Z is only 223; these numbers are in line with their theoretical counterparts (277 for Y and 218 for Z); the difference between the data and the theoretical predictions is not significant (Wilcoxon signed-rank test: p -value=0.22 and 0.38).²⁷ The results are very similar if we look at the median price in each round as opposed to the average price.²⁸

The average price of asset Y is higher than that of asset Z in all seven sessions of the experiment and in all rounds of each session.²⁹ Such difference in prices is statistically significant (Wilcoxon signed-rank test: p -value=0.01) and robust to both session and round effects.³⁰ That is, the departure from the Law of One Price in the laboratory is statistically significant. Note that the average spread between the price of Y and that of Z is 45, slightly lower than its theoretical counterpart, 59 (the difference is slightly significant, with a Wilcoxon signed-rank test p -value just above 0.05).³¹

Finally, as Table 6 shows, the average within-round standard deviation of transaction prices is relatively low: 7 for asset Z and 6 for asset Y .

²⁶As discussed in Section 3, we paid subjects only based on their earnings from the last ten rounds of Part III. Therefore, in the empirical analysis, we restrict ourselves to those rounds. The results for all 14 rounds of Part III are reported in Appendix V and are in line with those reported here. Results for Practice I and II are reported in Appendix VII.

²⁷See Table VIII.1.2, in Appendix VIII.

²⁸See Appendix IV.

²⁹Appendix VI shows the per-round statistics.

³⁰The results of non-parametric tests are reported in Appendix VIII.1. We also ran a batch of parametric tests in Appendix VIII.2, which allowed us to test for round and session effects; their results are largely the same as those of the non-parametric tests.

³¹See Table VIII.1.2, in Appendix VIII.

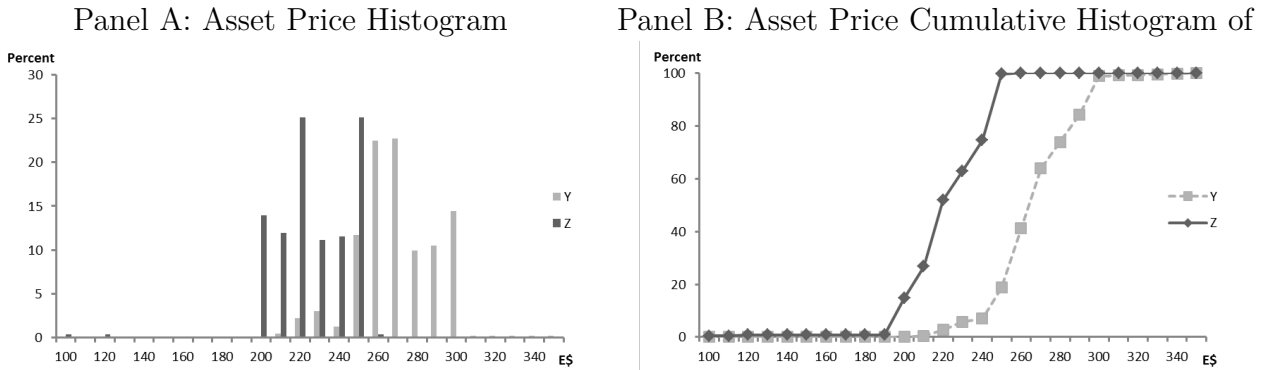
Table 6: Average Within-Round Asset Prices Standard Deviation.

	All Sessions	S1	S2	S3	S4	S5	S6	S7
Y	6	10	5	5	3	6	5	10
Z	7	6	2	6	3	15	5	11

This table shows the average within-round standard deviation of asset prices.

Figure 1 reports the histogram and the cumulative histogram of transactions prices throughout all rounds and sessions. Although the supports of the two distributions are not disjoint, the mass of the distribution of the price of asset Z is to the left of that of asset Y ; the p -value of a Kolmogorov-Smirnov Two-Sample Test conducted at the transaction level is 0.00.³² Indeed, looking at the cumulative histogram, we can see that the distribution of the transaction prices of Z first-order stochastically dominates that of asset Y . Furthermore, across all sessions, in 89 percent of rounds, the minimum transacted price of asset Y is greater than the maximum transacted price of asset Z .

Figure 1: Histogram and Cumulative Histogram of Asset Prices.



This figure displays the histogram (Panel A) and cumulative histogram (Panel B) of transaction prices for assets Y and Z .

A spread between asset Y and asset Z is not observed in Part II of the experiment, the second of the two practice sessions where subjects traded two assets but no borrowing was allowed.³³ Indeed, in Part II, the average spread across all sessions is only 6, and it is negative in two sessions out of seven. The difference between the price of asset Y and asset Z is not significant (Wilcoxon Sign-Rank test: p -value=0.30). Moreover, in 10 rounds out of 28 (four rounds for each of the seven

³²See Table VIII.1.3, in Appendix VIII.

³³Detailed results for Parts I and II are reported in Appendix VII.

sessions), the spread is non-positive, whereas, in our experiment, it is positive in all rounds.³⁴

4.3 Borrowing, Cash, and Collateral Value

In our theoretical model, the deviation from the Law of One Price arises because, in equilibrium, Buyers need collateral to borrow; since only asset Y can be used as collateral, they are willing to pay more for it than for asset Z . As mentioned in Section 4.2, the spread between the price of Y and that of Z observed in the laboratory is consistent with the theoretical predictions.

In this section, we study the extent to which the spread observed in the laboratory is generated by the same theoretical mechanism. For that to be the case, we should observe that i) Buyers in the laboratory were cash and borrowing constrained; and ii) whenever Buyers paid a higher price for asset Y than for asset Z , they did so because they needed the collateral. The data show this to be largely the case.

Table 7 shows the average borrowing per transaction on asset Y , across all paid rounds and sessions. The average borrowing per transaction is 86 and the median borrowing per transaction is 100, identical to its theoretical counterpart. More importantly, as the histogram in Figure 2 and the cumulative distribution in Table 8 show, in approximately 70 percent of transactions Buyers borrowed the maximum per transaction (100); in 88 percent of transactions, subjects borrowed more than 60 (above half of the collateral capacity of the asset).

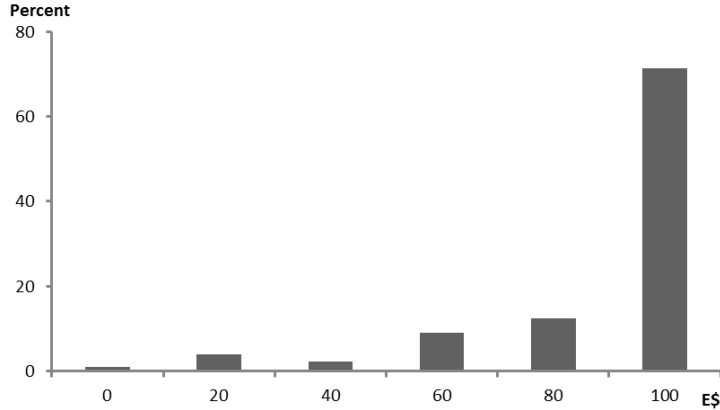
Table 7: Borrowing per Unit of Asset Y .

	All Sessions	S1	S2	S3	S4	S5	S6	S7
Mean	86	80	85	98	61	95	88	87
Median	100	100	100	100	62	100	100	100
Sd	25	32	27	7	21	11	28	24

This table shows the mean, median, and standard deviation, computed across all paid rounds of Part III, of the amount borrowed in asset Y transactions.

³⁴This argues against the possibility that our results are driven by uncontrolled behavioral biases. In particular, our findings are not driven by the way we presented information to participants, or the particular shapes (square and circle) we used, or the asymmetry in asset supply.

Figure 2: Histogram of Borrowing per Asset Y .



This figure displays the histogram of amount borrowed in asset Y transactions.

Table 8: Proportion of Y Transactions where Buyers Borrowed at Least a Given Amount.

E\$	1	20	40	60	80	100
Proportion:	0.99	0.97	0.93	0.88	0.73	0.7

This table shows the proportion of asset Y transactions where the Buyer borrowed at least a given amount.

Tables 9 shows average and median final cash holdings across all Buyers, rounds, and sessions. The average cash holdings equal 100 and are relatively stable across sessions.³⁵ Note that this is different from the value predicted by the theory (zero); nevertheless, since the average price of asset Z is 223 and that of asset Y is 268, Buyers' average final cash holdings are not enough to buy any more assets (even taking into account that they could borrow 100 on a purchase of asset Y).

Table 9: Buyers' Cash Holdings.

	All Sessions	S1	S2	S3	S4	S5	S6	S7
Mean	106	123	103	136	104	93	73	103
Median	101	150	150	100	151	64	10	150
Sd	101	96	101	130	96	86	85	83

This table shows the mean, median, and standard deviation of final cash holdings for Buyers.

An average borrowing of 86 and an average final cash holding of 100 do not necessarily imply a departure from the theoretical mechanism generating the spread between

³⁵We report Sellers' final cash holdings in Appendix IV.

assets Y and Z (that is, cash and borrowing constrained Buyers pay a higher price for Y because they need collateral). The reason is that, in the laboratory, assets Y and Z were indivisible; a Buyer may have borrowed less than (s)he could have or (s)he may have ended the round with some cash and still not be able to purchase additional units of asset Y or Z at the prevailing price in the round.

For this reason, in Table 10, we study the extend to which Buyers were constrained in the laboratory. Specifically, the first row of Table 10 reports the proportion of Buyers, across all sessions and rounds, who were unconstrained: Buyers whose final cash holdings plus any unused borrowing capacity was greater than the cost of buying an additional asset; in the table, i) unused borrowing capacity is the difference between how much a Buyer borrowed during the round and how much (s)he could have borrowed (that is, holdings of $Y * 100$ - total borrowing); and ii) the cost of buying an additional asset is the minimum between the average price of asset Z in the round and the average downpayment for Y in the round (the price of asset Y minus 100).³⁶

Table 10 shows that, on average, only 18 percent of Buyers were unconstrained in each given round; that is, in each round, on average, out of the six Buyers, approximately one could have bought more assets than (s)he actually did. Moreover, as the second and third row of the table show, the median Buyer was unconstrained only in one round out of ten, and less than 17% of Buyers were unconstrained in half of the rounds or more. Overall, the results suggest that, in most rounds, a very large proportion of Buyers were constrained even when looking at their cash holdings and unused borrowing capacity combined. This is consistent with the mechanism generating deviation from the Law of one Price in the theoretical model.³⁷

³⁶Note that we take the minimum between P^Z and $P^Y - 100$ only in those rounds where there Sellers have some unit of asset Y left to sell at the end of the round; in the other rounds, we consider just the average price of Z .

³⁷Appendix IX shows the results of a robustness check on the same statistics, where instead of using the round mean prices we use the quotes that Buyers were facing. The results are largely unchanged.

Table 10: Unconstrained Buyers

	Average	P10	P25	Median	P75	P90
Proportion	18.2%					
Number of Rounds per Buyer		0	0	1	3	5
Number of Buyers per Round		0	0	0.17	0.33	0.44

The first row of this table shows the proportion of unconstrained Buyers at the end of each round, that is, Buyers whose final cash holdings plus unused borrowing capacity (holdings of $Y \times 100$ - total borrowing) was greater than or equal to the minimum of the average price of asset Z and the average price of asset Y minus 100 (if Sellers still had any shares of Y left at the end of the round) in that round. The second row of the table shows summary statistics on the number of rounds when a Buyer was unconstrained. The third row of the table shows summary statistics on the number of Buyers that were unconstrained in a round.

Another way to test the theoretical mechanism generating the spread between Y and Z in the laboratory is to check whether when Buyers bought asset Y at a higher price than asset Z , they did so because they needed collateral to borrow.³⁸ The first row of Table 11 reports the proportion of Buyers, across all sessions and rounds, who paid for collateral capacity without using it, that is, the proportion of Buyers who bought at least one unit of asset Y at a price greater than the average price of Z in the round, and whose downpayment for that unit plus any final cash holdings was greater than the average price of asset Z .³⁹ As the table shows, on average, only 25 percent of Buyers in each round paid for collateral capacity without using it. Moreover, as rows two and three of the table show, the median Buyer could have afforded buying (her)his own asset allocation without borrowing only in two rounds out of ten; moreover, in the median round, 33 percent of Buyers paid for collateral capacity without using it.⁴⁰

In summary, the results of Tables 10 and 11 confirm that a positive collateral value is what generates a deviation from the Law of One Price in the laboratory: most Buyers needed to obtain collateral to borrow (in order to purchase more units of the risky asset) and hence were willing to pay a higher price for Y than for Z .

³⁸Assets Z and Y have identical payoff in all state of the world, and therefore, were it not for the different collateral capacities, there would be no reason for Buyers to buy Y when Z is cheaper (as they do in all rounds of the experiment).

³⁹For Buyers who bought more than one unit of asset Y we consider the last unit bought (the marginal unit).

⁴⁰Appendix IX shows the results of a robustness check on the same statistics, where i) instead of using the round mean prices we use the quotes that Buyers were facing; ii) when subjects bought more than one unit of asset Y , we take into account any unused borrowing capacity. The results are largely unchanged.

Table 11: Buyers who Paid for Collateral Capacity without Using it

	Average	P10	P25	Median	P75	P90
Proportion	0.25					
Number of Rounds per Buyer		0	1	2	4	5
Number of Buyers per Round		0	0.17	0.17	0.33	0.5

This table shows the proportion of Buyers who paid for collateral capacity without using it, that is, Buyers holding at least one unit of asset Y who paid for it more than the average price of Z in the round, and whose downpayment on Y plus additional cash holdings is greater than the average price of asset Z ; for Buyers who purchased more than one unit of Y , we consider the last unit bought. The second row of the table shows summary statistics on the number of rounds when a Buyer paid for collateral capacity without using it. The third row of the table shows summary statistics on the number of Buyers who paid for collateral capacity without using it in each round.

4.4 Asset Allocation

Table 12 shows the average final asset holdings per Buyer across all rounds and sessions of the experiment.⁴¹ ⁴² As in the theory, Buyers hold almost all the supply of the collateralizable asset Y : the average Buyer’s holding of Y is 0.91 and its median is 1, equal to its theoretical counterpart of 1. Buyers’ holding of asset Y is bigger than Seller’s holding of Y and the difference in holdings is statistically significant (Wilcoxon signed-rank test: p -value=0.01) and robust to both session and round effects.⁴³ Although the median Buyer’s holding of Z is also equal to its theoretical counterpart of 1, the average is only 0.58, reflecting the fact that some subjects only buy asset Y . Indeed, the distribution of Buyers’ holding of Y is to the right of that of Z , a statistically significant difference (Wilcoxon signed rank test: p -value=0.0078), robust to both session and round effects.⁴⁴

In our economy, Buyers value both asset Y and Z more than Sellers do, that is, there are gains from trade in the economy. In the theoretical equilibrium described in Section 2, such gains from trade are partially realized: Buyers buy all the supply of asset Y (one unit) and half the supply of asset Z (one unit out of two).

⁴¹Sellers’ final allocations are given by the overall asset supply minus Buyers asset allocations. We report them for completeness in Appendix IV.

⁴²In the model, there is a continuum of Buyers with mass one; since in Table 12 we report the average allocation per Buyer, we can directly compare the numbers with the theoretical predictions.

⁴³See Table VIII.1 in Appendix VIII.1.

⁴⁴See Appendix VIII.1 and VIII.2.

Table 12: Buyers' Final Holdings of Assets Y and Z .

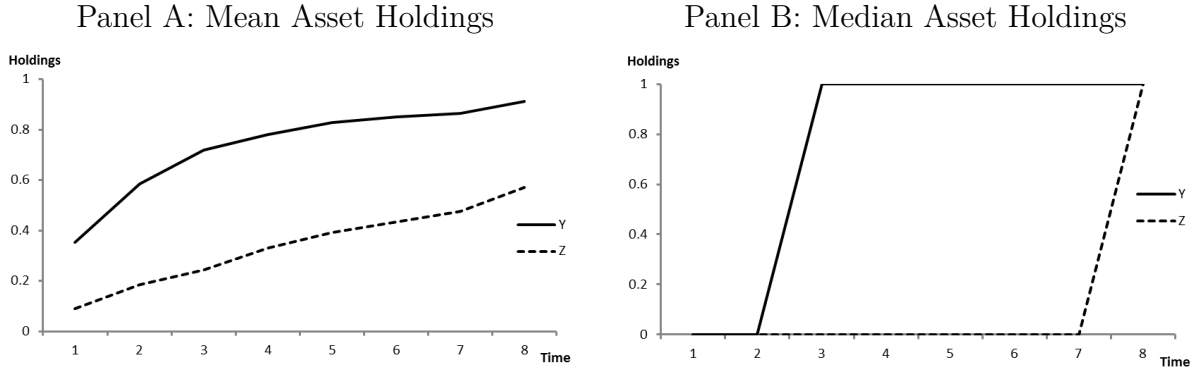
Panel A: Buyers' Final Holdings of Asset Y								
	All Sessions	S1	S2	S3	S4	S5	S6	S7
Mean	0.91	0.85	0.93	0.95	0.85	0.9	0.93	0.95
Median	1	1	1	1	1	1	1	1
Sd	0.74	0.71	0.76	0.86	0.9	0.66	0.61	0.67
Panel B: Buyers' Holdings of Asset Z								
	All Sessions	S1	S2	S3	S4	S5	S6	S7
Mean	0.57	0.65	0.53	0.43	0.52	0.77	0.65	0.5
Median	1	1	1	0	1	1	1	0.5
Sd	0.52	0.55	0.5	0.5	0.5	0.46	0.58	0.5

This table shows the mean, median, and standard deviation of end-of-the-round Buyers' holdings of assets Y (Panel A) and Z (Panel B).

We can gain further insight on how the market allocates the risky assets by looking at the evolution of holdings within a round. In Figure 3, we show the average/median Buyers' holdings of asset Y (solid line) and Z (dotted line) across all rounds and sessions, computed separately for each of eight twenty-second buckets.⁴⁵ As the figure shows, at each interval in the round Buyers hold a larger proportion of Y than of Z ; these differences between Buyers' holding of Y and Z are statistically significant (See Appendix VIII.4). This suggests that Buyers obtained asset Y at an earlier phase of the round as they wanted to exploit its collateral capacity; only at the end of the round they bought asset Z as they used the cash that was left to buy the cheaper asset.

⁴⁵The length of each trading round was 160 seconds.

Figure 3: Buyers' Asset Holdings over Time within Rounds.



This figure displays the mean and median (Panels A and B respectively) Buyers' holdings of assets Y and Z within each 20-second interval of the trading period. Each point on a graph shows the average for that time interval across all paid rounds.

4.5 Laboratory Outcomes Over the Experimental Rounds

It is interesting to study how laboratory outcomes evolve over the experimental rounds.

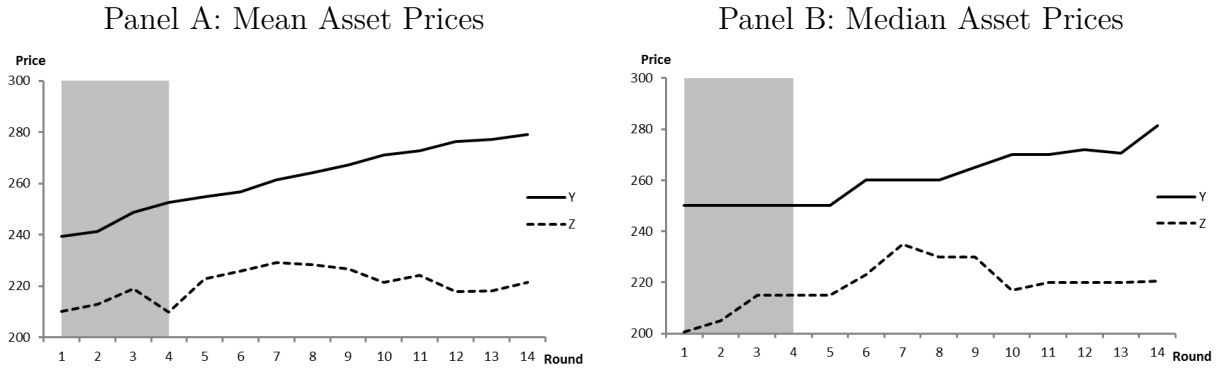
In Figures 4-6, we report the average/median (Panel A/Panel B) prices (Fig. 4), borrowing per asset Y (Fig. 5) and Buyers' asset holdings across sessions (Fig. 6), computed separately for each round of trading (including the first four non-paid practice rounds, shaded in the chart). Figures 5 and 6 show that borrowing per asset Y and asset holdings are stable across rounds, close to the value described above (and to the prediction of the theoretical model) from the very first rounds. That is, from the beginning (even in the practice rounds), subjects understood that borrowing was useful, and that there were gains from trade to be exploited.⁴⁶

In contrast, price behavior is not stable through the rounds. The spread between asset prices is positive from the first round (reflecting the fact that Buyers from the beginning understood that collateral was valuable). However, whereas the price of asset Z is relatively stable across rounds, there is a clear upward trend in the price of the collateralizable asset Y (a Wilcoxon signed-rank test on the difference between mean prices in the first four rounds and the last four rounds of the experiment yields

⁴⁶In Appendix VIII.3, we report a series of non parametric tests on learning, that is, on the difference between the first four rounds and the last four rounds of the experiment. We do not find any statistical difference for asset allocation and borrowing.

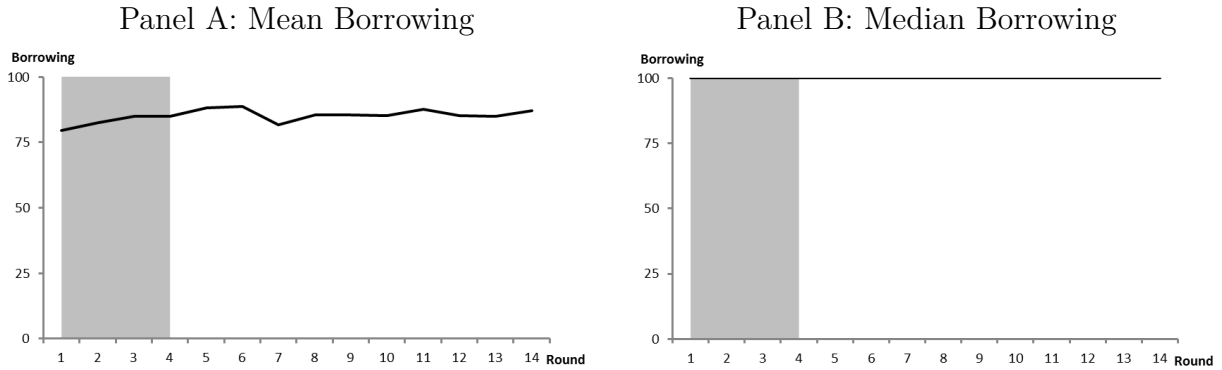
p -values of 0.15 for asset Z and 0.02 for asset Y). Although Buyers wanted to borrow from the very first rounds (and hence they bought asset Y), competition among them drove the price up more and more as the experiment progressed. In other words, subjects in the experiment understood the fact that borrowing was useful from the beginning, but they discovered its equilibrium value through trading activity as the experiment progressed.

Figure 4: Asset Prices over Rounds.



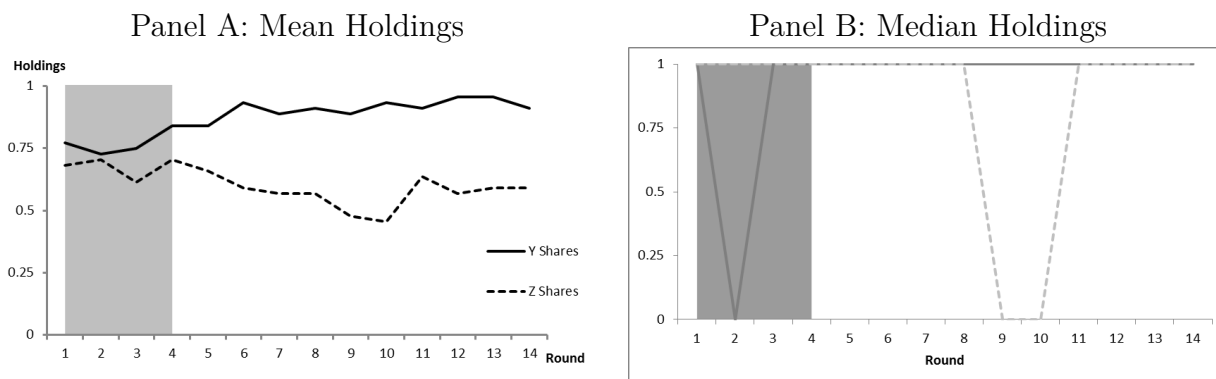
This figure displays the mean and median (Panels A and B respectively) transaction prices of assets Y and Z in each of the fifteen rounds of Part III of the experiment across all sessions. Note that the first four rounds (shaded) are practice rounds.

Figure 5: Borrowing Per Asset Y over Rounds.



This figure displays the mean and median (Panels A and B respectively) amount borrowed per traded asset Y within each of the fifteen rounds of Part III of the experiment across all sessions. Note that the first four rounds (shaded) are practice rounds.

Figure 6: Buyers' Asset Holdings over Rounds.



This figure displays the mean and median (Panels A and B respectively) for Buyers' holdings of assets Y and Z within each of the fifteen rounds of Part III of the experiment across all sessions.

Note that the first four rounds (shaded) are practice rounds.

5 Conclusion

This is the first paper to study, in a controlled laboratory environment, the effect of leverage on asset prices and its role in creating deviations from the Law of One Price. To this purpose, we develop a model of leverage that is amenable to laboratory implementation and collect experimental data. In the theoretical model, agents trade two securities with identical payoffs but different collateral capacities; the asset that can be used as collateral fetches higher prices than the asset that cannot, creating a deviation from the Law of One Price.

In the laboratory financial market, subjects trade the two assets in a double auction. The two assets have identical payoffs, thereby allowing us to test for the presence of collateral value and for deviations of the Law of One Price directly. In the laboratory, the asset that can be used as collateral fetches a higher price, as the theory predicts. The spread between collateralizable and non-collateralizable assets is significant and quantitatively close to theoretical predictions. Moreover, the spread between the prices of the two assets stems from the fact that subjects are cash and borrowing constrained, that is, from the same theoretical mechanism highlighted by the theory. Finally, consistent with the predictions of the theory, leverage allows gains from trade to be realized to a greater extent in the laboratory: when leverage is possible, agents who value the asset the most end up holding more of it.

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