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Collateral Constraints and the Law of One Price: An Experiment

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ABSTRACT

We test the asset pricing implications of collateralized borrowing (that is, of using assets as collateral to borrow money) in the laboratory. To this purpose, we develop a general equilibrium model with collateral constraints amenable to laboratory implementation and gather experimental data. In the laboratory, assets that can be leveraged fetch higher prices than assets that cannot, even though assets' payoffs are identical in all states of the world. Collateral value, therefore, creates deviations from the Law of One Price. The spread between collateralizeable and noncollateralizeable assets is significant and quantitatively close to theoretical predictions.

THE 2008 FINANCIAL CRISIS HIGHLIGHTED THE limited understanding of the role of leverage in financial markets among both academics and practitioners.[1] As a result, in the years following the crisis, a strand of the theoretical financial literature focused on the impact of leverage on asset prices.[2] During the crisis, it also became apparent that cross-sectional differences in asset prices were related to heterogeneity in asset collateral capacities. Several theoretical papers study the cross-sectional implications of collateralized borrowing in a world where agents are heterogeneous and markets are incomplete: for instance, Fostel and Geanakoplos (2008) in a collateral general equilibrium model, Garleanu and Pedersen (2011) in a CAPM model, and Brumm et al.

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[1] See, for example, Brunnermeier (2009), Geanakoplos (2010b), and Gorton (2009).

[2] See, 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 (2010a), and Simsek (2013). Early studies on the effect of leverage constraints on asset prices were published before the crisis, see, for instance, Hindy (1995) for a partial equilibrium model, and Geanakoplos (1997, 2003) for a general equilibrium model with incomplete markets.

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(2015) in an infinite-horizon exchange economy. These papers show that collateral value increases asset prices, creating deviations from the Law of One Price.[3]

Fostel and Geanakoplos (2008) show that when an asset can be used as collateral, its price can be decomposed into two parts, its payoff value and its collateral value. The payoff value reflects the owner's valuation of the asset's future cash flow. The collateral value reflects the owner's valuation of being able to leverage the asset, that is, of being able to use it 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.[4] A well-documented example of such deviations is the so-called "CDS-bond basis," the price difference between Treasuries and covered CDS positions.[5]

In this paper, we study the impact of collateral constraints on asset prices in a controlled experiment. In the laboratory, we can study assets with identical payoffs that differ only in their collateral capacities; this cannot be done with field data (for instance, even when comparing Treasuries to covered CDS positions, counterparty risk muddies the water).[6]

To this purpose, we build a model of a financial economy, amenable to laboratory implementation, with incomplete markets, heterogeneous agents, and collateralized borrowing. Agents trade two risky assets with identical payoffs in all states of the world. Agents can borrow only by posting collateral, and only one of the two assets can be used as collateral. In equilibrium, collateral is valuable because agents who value the risky assets the most are constrained, and collateral allows them to borrow and purchase more risky assets. For this reason, the price of the collateralizeable asset is higher than the price 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. Finally, since agents need to post collateral to borrow and collateral is scarce, the equilibrium fails to implement the Pareto-efficient allocation, in which the agents with the highest asset valuation own all of the risky-asset supply.

We bring the model to the laboratory by having students play in a two-asset double auction experiment with collateralized borrowing, and we gather

[3] Other drivers of deviations from the Law of One Price, similar to collateral, are the "divertibility premium" under incentive problems in Biais, Hombert, and Weill (2017) and the "liquidity premium" in new monetarist papers such as Lagos (2010), Li, Rocheteau, and Weill (2012), and Lester, Postlewaite, and Wright (2012).

[4] An early example of collateral value generating deviations from the Law of One Price can be found in Geanakoplos (2003).

[5] A covered CDS consists of simultaneously holding a CDS and its underlying bond. Since the CDS insures against the default of the bond (e.g., a corporate bond), the payoff of the covered CDS position equals that of a riskless bond (e.g., a Treasury). However, since agents can borrow more using a riskless bond than using the covered CDS as collateral, riskless bonds generally trade at a positive spread over covered bond positions.

[6] Moreover, data on loan terms for securities used as collateral are only now beginning to be collected in the United States on a limited basis. See, for instance, Baklanova et al. (2017).

experimental data. In the experiment, we also elicit subjects' risk aversion using the Holt and Laury (2002) methodology and compare experimental outcomes with theoretical predictions based on the elicited levels of risk aversion.

The experimental results confirm the theory's main prediction: the price of the asset that can be used as collateral is higher than the price of the asset that cannot. Subjects are willing to pay more for the collateralized asset even though the two assets have identical payoffs, that is, collateral value creates a deviation from the Law of One Price in the laboratory. The spread between the two assets is significant and quantitatively close to what theory predicts. Moreover, the spread seems to arise for the same reason highlighted by the theory: in the laboratory, a large fraction of subjects are willing to pay for collateral because they are borrowing constrained; the collateralizeable asset allows them to borrow and increase their holdings of risky assets. Last, final asset holdings are close to their theoretical counterparts, and, as theory predicts, the allocation is not Pareto efficient: although agents with the highest asset valuation buy all the supply of the collateralized asset, they share the supply of the noncollateralized asset.

A large and important literature in experimental finance, starting with Smith (1962), tests asset pricing models in a controlled laboratory environment where subjects trade in a double auction. This literature generally finds that double-auction markets converge to the competitive equilibrium of the underlying model.[7,8] Convergence to the collateral equilibrium, however, cannot be taken for granted in our environment. In the models tested in the traditional experimental finance literature (e.g., the CAPM), equilibrium is the solution to a single system of equations, and tatonnement adjustment converges. In contrast, in our model, finding the collateral equilibrium requires a guess on which system of equations defines the equilibrium itself, and tantonnement convergence is not guaranteed.

Nevertheless, we find that, from the very first rounds of trading, subjects borrow the maximum, and there are significant deviations from the Law of One Price (as the collateral equilibrium predicts). Moreover, as subjects become more acquainted with the experiment over the rounds, prices and quantities approach their theoretical counterparts: a larger fraction of the collateralizeable assets are purchased by those who value collateral the most. As subjects discover the value of collateral, the price of the collateralizeable asset increases, and the spread between the collateralizeable asset and the noncollateralizeable asset converges toward its equilibrium level.

[7] For a discussion, see Plott (2008), Bossaerts and Plott (2008), and Asparouhova, Bossaerts, and Plott (2003).

[8] The effect of leverage on asset price bubbles has been studied in a double auction by King et al. (1993) and more recently Haruvy and Noussair (2006) and Füllbrun and Neugebauer (2012). However, as is often the case in the bubble literature, their experimental designs do not embed the theoretical mechanisms through which bubbles arise and leverage affects asset prices (indeed, King et al. (1993) conjecture that, similar to the effect of allowing short sales, leverage should dampen bubbles). As a result, the effect of leverage on asset price bubbles observed in the laboratory does not correspond to a theoretical equilibrium outcome.

As we mention above, in the theoretical model, collateral is valuable because subjects face binding collateral constraints. Consistent with this result, we find that as convergence to the collateral equilibrium occurs—and deviations from the Law of One Price become more pronounced—the proportion of subjects who are constrained (although positive from the beginning) increases. Furthermore, convergence to collateral equilibrium could not occur without subjects' willingness to accept—that is, not to attempt to arbitrage away—price differences between the two assets (which are not real arbitrage opportunities); as the experiment progresses and the spread between prices increases, such attempts become less frequent.

The paper is organized as follows. Section I develops the theoretical model. Section II describes the experiment design and the experimental procedures. Section III presents the results. Section IV concludes. All supplementary material is presented in the Internet Appendix.[9]

I. Theory

A. The Model

We model an economy in which agents' ability to leverage assets affects their prices. Our model retains the main features of the theoretical literature, namely, market incompleteness, agent heterogeneity, and collateral as a repayment enforcement mechanism (e.g., Fostel and Geanakoplos (2008)) but is amenable to laboratory implementation. In the economy, two identical risky assets are traded, but only one of them can be used as collateral to borrow money. A spread between the prices of the two assets arises due to the presence of collateral value.

A.1. Time and Assets

We consider a two-period economy, with time $t = 0, 1$. At time 1, there are two states of the world, $s = High$ and $s = Low$, which occur with probability q and $1 - q$. There is a continuum of agents of two different types, indexed by $i = B, S$, which denote 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. The two risky assets have identical payoffs. In state Low, the assets pay D_{Low} to both Buyers and Sellers. In state $High$, the assets pay more to Buyers than to Sellers, that is, $D^B_{High} > D^S_{High}$. Moreover, for each type i, the payoff in the high state of the world is always higher than the payoff in the low state of the world, that is, $D^i_{High} > D_{Low}$, for $i = B, S$.[10] The difference in payoffs can be interpreted as Buyers and Sellers owning

[9] The Internet Appendix may be found in the online version of this article.

[10] This is similar to the way gains from trade arise in the double-auction literature; see, for instance, Smith (1962), Plott and Sunder (1982), and subsequent papers.

different technologies that affect the assets' productivity. As in the theoretical literature, the presence of agent heterogeneity is crucial for leverage to affect trading activity and asset pricing.[11]

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

A.2. 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.[12]

More precisely, we assume that agents can borrow from a financial institution (a bank) only on secured terms by posting asset Y as collateral.[13] Furthermore, we 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.[14] 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.[15]

In other words, agents can leverage asset Y (by buying the asset and using it as collateral to borrow money at the time of the purchase), but cannot leverage asset Z. 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.

[11] In Fostel and Geanakoplos (2008), heterogeneity is modeled as differences in subjective probabilities over states of the world. In Garleanu and Pedersen (2011), heterogeneity is modeled as differences in risk aversion. Differences in subjective probabilities, asset payoffs, risk aversion, and wealth all create the same effect of leverage on asset prices due to collateral value; for a detailed discussion, see Fostel and Geanakoplos (2014). Our model allows for several forms of agent heterogeneity: different asset payoffs, different levels of risk aversion, and different endowments. As we discuss in Internet Appendix Section II, the parameter specification presented in Table I was chosen to make the experimental implementation both simpler for the subjects and suited to answering our research questions.

[12] A real-world example of this is the so-called CDS-bond basis, widely discussed in the empirical finance literature. In particular, Y and Z can be thought of as a riskless bond and a covered CDS—two positions with identical payoffs but with different collateral capacities (see Footnote 5).

[13] The purpose of our paper is to study the effect of leverage on asset prices in the laboratory. To 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).

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

[15] These 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 were positive, leverage would still increase asset prices (see, for example, Fostel and Geanakoplos (2012a) and Simsek (2013)).

Table I
Parameter Values

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

Payoffs	D_{Low}		D^B_{High}		D^S_{High}	q
Values	100		750		250	0.8
Endowments	m^B	m^S	a^B_Y	a^B_Z	a^S_Y	a^S_Z
Values	400	0	0	0	1	2

A.3. 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^i_Y and a^i_Z units of the risky assets. Agent i has a CRRA payoff function for state $s = High,\ Low$, given by

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

where $x_s = w + D^i_s(y + z) - \varphi$. In the last expression, w denotes final cash holdings, y and z denote final asset holdings, $D^i_s(y + z)$ denotes dividends accruing from asset holdings in state s, and φ is total debt repayment. Agents' attitudes toward risk are 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

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

Agents take asset prices p_Y and p_Z as given and choose asset holdings $y \geq 0$ and $z \geq 0$, cash holdings $w \geq 0$, and borrowing $\varphi \geq 0$ to maximize (2) subject to the budget constraint (3) and the collateral constraint (4):

$$w + p_Y y + p_Z z \leq m^i + p_Y a^i_Y + p_Z a^i_Z + \varphi, \tag{3}$$

$$\varphi \leq D_{Low} y. \tag{4}$$

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).

B. Equilibrium Analysis

In order to study the asset pricing implication of collateralized borrowing, we discuss the equilibrium for the parameterization implemented in the laboratory, reported in Table I.

Under this parameterization, the assets' payoff in state *Low* is $D_{Low} = 100$; in state *High*, it is $D^B_{High} = 750$ for Buyers and $D^S_{High} = 250$ for Sellers. The

Table II
Equilibrium in the Risk-Neutral Case

This table reports the equilibrium for $\beta_i = \beta = 1$.

	Asset Prices	
p_Y		285
p_Z		220
Spread		65
	Allocations	
	Buyers	Sellers
y	1	0
z	0.98	1.02
φ	100	0
w	0	500

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 endowments. Note that since Buyers have all the cash endowment and Sellers have all the asset endowment, Buyers are on the demand side and Sellers are on the supply side of the asset market.[16]

Table II presents the equilibrium values in the risk-neutral case, $\beta_i = \beta = 1$. Note that the model does not admit a closed-form solution. To find the equilibrium for the parameters in Table I, we guess an equilibrium regime (we take a stand on which constraints are binding for each type of agent), solve the system of equations implied by the assumed regime, and finally check whether the solution to the system of equations is a genuine equilibrium.[17]

In equilibrium, 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 have identical payoffs in all states of the world, this spread represents a deviation from the Law of One Price.

Equilibrium individual decisions are reported in the lower part of Table II.[18] Buyers use all of their cash endowments and borrowing capacity to buy all the assets they can afford. The solution to their optimization problem is a corner solution since their expected value of both risky assets $(0.8(750) + 0.2(100) = 620)$ is higher than equilibrium prices. As a consequence, Buyers buy asset Y by leveraging the purchase and buy asset Z free of debt: they borrow the maximum they can using one unit of Y as collateral, 100, and use all their cash endowment of 400 to pay for the down payment of one unit of Y and 0.98

[16] See Internet Appendix Section II for a more detailed discussion of the parameter specification of Table I.

[17] See Internet Appendix Section I.A for a discussion on how to solve for the equilibrium and for a proof that the equilibrium is unique.

[18] In the experiment, the assets are not perfectly divisible, and thus we use as the theoretical benchmark the closest integer approximation.

units of Z. Buyers are indifferent between using one extra unit of cash to buy Z or as a down payment to buy Y because the expected returns of these two investments are the same (see Internet Appendix Section I.A).

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 because their expected value is lower than the price of 285.

Finally, assets change hands from Sellers (to whom the assets pay less) to Buyers (to whom the assets pay more), thereby realizing some, but not all, of the gains from trade in the economy. Buyers end up holding all the supply of Y and share the supply of Z with Sellers. For this reason, collateral equilibrium does not implement the Pareto-efficient allocation, in which Buyers own the total supply of both assets Y and Z in the economy.[19,20] The allocation is not Pareto efficient because Buyers need to post collateral, and collateral is scarce; as a result, they cannot borrow as much as they want and purchase all the supply of risky assets.

B.1. Collateral Constraints, Collateral Value, and the Law of One Price

In our model, the equilibrium prices of two assets with identical payoffs *in all states 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 not only serve as investment opportunities (i.e., they give a right to a future cash flow), but they also allow investors to borrow money. When collateral constraints are binding, deviations from the Law of One Price arise due to collateral value.

Let us explain why, in our model, there is a spread between asset prices in equilibrium. Consider the equilibrium presented in Table II. At asset Z's price, Buyers' expected marginal payoff of investing one unit of cash at time 0 in asset Z is given by $\frac{E(Z)}{p_Z} = \frac{620}{220} = 2.82$. Since the marginal payoff of a unit of cash at time 0 is greater than one, borrowing is valuable: for each unit of cash they borrow, Buyers get an additional payoff of $2.82 - 1 = 1.82$ at time 1. For this reason, Buyers would like to borrow to invest in asset Z, but the only way to borrow is to buy Y and post it as collateral. If $p_Y = p_Z$, Buyers would only buy asset Y (because it allows them to borrow); given their budget constraints, this would violate market clearing. Hence, the price of Y must be higher than that of asset Z.

How large should the spread between the prices of assets Y and Z be? It should be equal to the value Buyers attach to asset Y's collateral capacity (its

[19] By transferring Sellers' equilibrium holdings of the risky assets to Buyers, everybody can be made better off (after transfers), given that in Buyers' hands the assets pay 750 instead of 250 in the high state.

[20] Here and in the rest of the paper, by Pareto-efficient allocation we refer to the unconstrained efficient allocation.

Table III
Equilibrium for Different Levels of Risk Aversion

This table reports the equilibrium for different values of β.

	Risk Averse					Risk Neutral	Risk Loving	
β	−0.25	0.00	0.25	0.50	0.75	1.00	1.25	1.50
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	0.97	0.96	0.94
φ^B	69	100	100	100	100	100	100	100
w^B	0	0	0	0	0	0	0	0

collateral value). This is indeed the case. For each unit of asset Y, Buyers can borrow 100; for each unit of cash they borrow, they get an additional expected payoff of 1.82 at time 1, which discounted by the marginal payoff of cash is $\frac{1.82}{2.82}$. Therefore, borrowing 100 generates an additional expected payoff at time 0 of $100\frac{(1.82)}{2.82} = 65$, the spread between the prices of assets Y and Z.[21]

B.2. The Case with Risk Aversion

The most salient feature of the equilibrium described above is the deviation from the Law of One Price. This deviation does not hinge on agents' risk neutrality. Table III presents the equilibrium for different values of risk aversion.[22]

Note that the spread in prices is decreasing in the level of risk aversion. For extreme values of risk aversion ($\beta = -0.25$), the spread disappears since Buyers are less willing to hold risky assets and hence the collateral constraint ceases to bind. 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.

For the other levels of risk aversion reported in the table, Buyers' collateral constraint is binding and a deviation from the Law of One Price (a spread between the prices of Y and Z) arises in equilibrium.[23] In these cases, agents' choices in equilibrium are as described above for the risk-neutral case: Buyers borrow to the maximum, hold no cash at the end of the round, buy all the supply of Y, and share asset Z with Sellers.

[21] As we mentioned in the introduction, Fostel and Geanakoplos (2008) provide a general decomposition of the price of a collateralizeable asset into *payoff value* (the present discounted value of the expected marginal utility of holding the asset) and *collateral value* (the amount agents are willing to pay for the asset's collateral capacity). In our model, the spread between the prices of assets Y and Z equals the *collateral value* as defined in Fostel and Geanakoplos (2008).

[22] See Internet Appendix Section I.B for a discussion on how to solve for the equilibrium for the different values of β in Table III, as well as for a discussion on uniqueness.

[23] The spread becomes positive for any level of β greater than −0.16, a relatively high level of risk aversion.

II. The Experiment

A. Experiment Design

The experiment was run at the Interdisciplinary Center for Economic Science (ICES) at George Mason University. We recruited students across all disciplines at George Mason University using the ICES online recruiting system.[24] Subjects had no previous experience with the experiment. The experiment was programmed and conducted with the software z-Tree (Fischbacher (2007)).

The experiment consisted of seven sessions. Twelve subjects participated in each session, except in Session 3, when 16 subjects participated, for an overall total of 88 subjects.

In each session, we implemented the two-asset economy with collateralized borrowing described in Table I. Each session of the experiment consisted of 10 paid rounds in which subjects traded in a double auction. Before the 10 paid rounds, we had subjects practice the experimental procedures by playing for 10 unpaid rounds: in the first two unpaid rounds, subjects played in a one-asset economy; in the following four unpaid rounds, they played in a two-asset economy with no borrowing; in the last four unpaid rounds, they played using the same procedures as in the 10 paid rounds of the main experiment.

In the next subsection, we describe the procedures for the 10 paid rounds; the procedures for the 10 unpaid rounds are similar.[25]

B. Experimental Procedures

At the beginning of the experiment, subjects read the experimental instructions on their computer screens. As part of the online instructions, subjects 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 the experimenters questions, which were answered in private. Subjects were also given a "reference sheet" with a summary of the experimental procedures that they could consult during the experiment.

(1) All payoffs were denominated in an experimental currency called the experimental dollar, $E\$$. In the laboratory, the risky assets were referred to as "widgets"; asset Z was called a CIRCLE widget, and asset Y a SQUARE widget.
(2) 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

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

[25] In Internet Appendix Section X, we provide the instructions, screenshots, and "reference sheets" used in the experiment. Note that, in the material given to subjects, the first two unpaid practice rounds (one asset economy) were referred to as Session I of the experiment; the following four unpaid practice rounds (two-asset economy with no borrowing) were referred to as Session II of the experiment; finally, the last four unpaid practice rounds together with the 10 paid rounds (two-asset economy with collateralized borrowing) were referred to as Session III of the experiment.

Sellers. Subjects could see their role in the left corner of their computer. Subjects maintained the same role throughout the experiment.

(3) 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.

(4) Subjects traded the two assets by exchanging them among themselves for 160 seconds. They used the trading platform shown in Internet Appendix Section X.

(5) 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.

(6) 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.

(7) To post a Buy Offer for asset Z, a Buyer would enter the price (s)he was willing to pay. 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.[26] Similarly to Sell Offers, Buy Offers appeared immediately on everyone's screen, in a separate table for each market. In the experiment, Borrowing was referred to as a "Cash Transfer" and the role of the Bank was played by the experimenters. Buyers and Sellers could cancel their offers at any time.

(8) A trade occurred if the best Sell Offer was less than or equal to the best Buy Offer. This situation was recognized by the system, and the trade took place automatically at the price of the outstanding offer.

(9) After the 160 seconds elapsed, the state of the world was realized.[27] Subjects' payoffs were then 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 (for Buyers) any debt repayment. Since purchasing asset Y while borrowing at the same time is a complicated task, Buyers received feedback after each round on how their payoff related to their trading and borrowing decisions given asset Y's average price in the round (see Internet Appendix Section X).[28]

(10) After round 1 ended, a new round started. The experiment continued until all 10 rounds were played. Each round was independent from the

[26] A 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 down payment was less than the cash available to the Buyer.

[27] The state of the world was randomized subject to the constraint that, in each session, eight high rounds out of the 10 paid rounds would occur.

[28] We did not provide any feedback to Sellers nor did we provide feedback on Buyers' purchases of asset Z because trading procedures for Sellers and for Buyers when trading asset Z were much simpler.

Table IV
Holt and Laury Scores

This table reports the median, 25th percentile, 75th percentile, and mean of the number of safer choices made by subjects out of the 10 questions on the Holt and Laury (2002) questionnaire, both across all subjects and for Buyers and Sellers separately. The table also reports the *p*-value of a two-sample Wilcoxon rank-sum test on the null that Buyers' and Sellers' scores have the same median.

	Median	25th Percentile	75th Percentile	Mean
Buyers	5	4	6	5.14
Sellers	5	4	6	5.41
Overall	5	4	6	5.27

Wilcoxon Rank-Sum Test for "Buyers' Score = Sellers' Score": p-value = 0.452

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 of the 10 paid rounds for payment purposes. The payoff of that round was converted into cash at the rate of \$1 per E\$30. After trading ended, we elicited each subject's risk aversion using the Holt and Laury (2002) procedure (see Internet Appendix Section III for a description of the procedure). Subjects were paid on average \$31 in the double auction phase of the experiment and on average \$3 in the elicitation phase of the experiment.

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

III. Results

A. The Theoretical Benchmark

In analyzing our empirical results, we compare subjects' choices in the laboratory with the predictions of the theoretical model in Section I. To do so, we need to take a stand on the level of risk aversion in the laboratory. We do this by eliciting each subject's risk aversion using the Holt and Laury (2002) procedure at the end of the double auction. In the Holt and Laury (2002) procedure, each subject makes 10 binary choices between two lotteries, one safer and one riskier. Assuming that subjects have a CRRA utility function (as in our model), Holt and Laury (2002) map the number of safer choices a subject makes in the laboratory to an interval for a subject's risk-aversion parameter β.[29]

As Table IV shows, across all sessions, the median number of safer choices across subjects is 5.[30] This implies that subjects' median risk-aversion parameter β belongs to the interval (0.59,0.85), with a midpoint of 0.72; Holt and Laury

[29] See Tables IA.I and IA.II in Internet Appendix Section III.

[30] In Table IA.III in Internet Appendix Section III, we report the same results as in Table IV by session. Note that, in Tables IV and IA.III, we follow Holt and Laury's (2002) suggestion of simply counting the number of safer choices, irrespective of inconsistencies. Table IA.IV in Internet

Table V
Holt and Laury Scores by Session

This table reports the median Holt and Laury (2002) score by session, both across all subjects and for Buyers and Sellers separately; the table also reports the results of a series of Wilcoxon rank-sum tests on the nulls that, in a given session, subjects' median score equals the median score of subjects in all the other sessions.

	Median Scores						
	S1	S2	S3	S4	S5	S6	S7
Buyers	5	4.5	5	4.5	5.5	5	5.5
Sellers	6	5	5.5	4.5	5.5	5	5.5
Overall	5	5	5	4.5	5.5	5	5.5
Wilcoxon rank-sum test p-values	0.597	0.387	0.591	0.373	0.451	0.985	0.273

(2002) refer to such a level of risk aversion as "Slightly Risk Averse." The 25th percentile of the number of safer choices is 4, which corresponds to the interval (0.85,1.15), with a midpoint of 1 (risk neutrality); whereas the 75th percentile is 6, which corresponds to the interval (0.32, 0.59), with a midpoint of 0.46 ("Risk Averse" in the Holt and Laury (2002) classification). Consistent with the fact that we randomly assigned subjects to the roles of Buyers and Sellers, there is no significant difference between the number of safer choices of Buyers and Sellers (the p-value of a rank-sum test is 0.452). Moreover, in Table V, we report subjects' median scores by session: in four sessions of seven, the median score is 5, and across sessions it ranges from 4.5 to 5.5; indeed, none of the sessions have a median Holt and Laury (2002) score significantly different from that of all the other sessions (the p-values of a series of rank-sum tests on the nulls that, in a given session, subjects' median score equals the median score of the subjects in all the other sessions range from 0.273 to 0.985).[31]

In order to establish the theoretical benchmark against which to measure the experimental results, one would ideally compute a different collateral equilibrium for each session using the individual Holt and Laury (2002) scores. However, as we mentioned in Section I.B, our model does not admit a closed-form solution. To find the equilibrium, we guess an equilibrium regime (we take a stand on which constraints are binding for each type of agent), solve the system of equations implied by the assumed regime, and finally check whether the solution to the system of equations is a genuine equilibrium. As a result, finding the equilibrium using the individual Holt and Laury (2002) scores of each of the 12 (or 16 in Session 3) subjects participating in each session

Appendix Section III reports the same results as Table IV after excluding subjects with multiple switching points. The median and average risk-aversion scores are very similar to those reported here.

[31] Note that since each subject answered the Holt and Laury (2002) questionnaire on his/her own, there is no meaningful dependence across subjects within a session. For this reason, we ran the tests on subjects' individual scores; although this increases the power of the test, we still do not find significant differences across sessions and roles.

Table VI
Equilibrium for Different Values of β

This table reports the equilibrium prices and holdings at the midpoint of the risk-aversion intervals corresponding to the 25th, 50th (median), and 75th percentiles of subjects' responses to the Holt and Laury (2002) procedure.

	25th Percentile	Median	75th Percentile
Number of Safe Choices	4	5	6
Holt and Laury Description	Risk Neutral	Slightly Risk Averse	Risk Averse
β	1	0.72	0.455
p_Y	285	277	265
p_Z	220	218	217
Spread	65	59	48
y^B	1	1	1
z^B	1	1	1
φ^B	100	100	100
w^B	0	0	0

is highly unpractical.[32] For this reason, we use as our theoretical counterpart the equilibrium corresponding to the median level of risk aversion.

Note that we could allow for different levels of risk aversion for Buyers and Sellers; we choose not to do so since, as we mention above, there is no statistically significant difference between the medians of Buyers' and Sellers' scores. Similarly, we do not compute a different equilibrium in each session using the median risk-aversion score of that session because we do not find any significant difference across sessions.

Finally, as a robustness check, Table VI presents the equilibria at the midpoint of the risk-aversion intervals corresponding to the 25th percentile, the median, and the 75th percentile of the number of safer choices.[33] In all equilibria, Buyers borrow the maximum (100) to buy all the supply of asset Y and half the supply of asset Z. More importantly, in all equilibria, there is a deviation from the Law of One Price; additionally, the spread between the prices of assets Y and Z is always roughly 20% of the price of asset Y.[34]

Given these similarities across equilibria, from now on, we just use as our theoretical benchmark the equilibrium prediction for the midpoint of the interval corresponding to the median number of safer choices across all subjects, that is, $\beta = 0.72$.[35] Compared to the risk-neutral case described in

[32] Indeed, the collateral general equilibrium literature usually assumes either two types of agents or a continuum of types.

[33] Final asset holdings have been rounded to the nearest unit to reflect the fact that assets are indivisible in the laboratory. Buyers' equilibrium holdings of asset Z are 1.08, 1.02, and 0.97 for β equal to 0.455, 0.72, and 1.

[34] One could object that equilibrium outcomes could be more severely impacted if only one type of agent (Buyers or Sellers) were to be more risk averse or more risk loving than the other. For this reason, as a further robustness check, in Table IA.V of Internet Appendix Section III, we recompute equilibrium outcomes for all possible combinations of Buyers' and Sellers' scores at the 25th, 50th (median), and 75th percentiles. The results are close to those reported in Table VI.

[35] The equilibrium is discussed in detail in Internet Appendix Section I.B.

Table VII
Average Asset Prices

This table reports the means and standard deviations (in parentheses) of the transaction prices of assets Y and Z and the spreads between them, across all paid rounds of all sessions and by session.

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

Section I.B, the prices of both assets Y and Z are slightly lower (277 and 218, vs. 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 ($\varphi^B = 100$) 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 the supply of asset Z ($z^B = 1$).

B. Asset Prices and Deviation from the Law of One Price

Although Y and Z have identical payoffs in all states of the world, in the laboratory the price of the collateralizable asset Y is greater than that of Z.[36] As the theory predicts, deviations from the Law of One Price arise due to the presence of collateral value.

As we discuss in Section II, we paid subjects based on their earnings from the last 10 rounds of the experiment. Therefore, in all the empirical analysis, unless we explicitly state otherwise, we report results from those rounds only.[37] Table VII reports the average prices of the two assets across transactions, rounds, and sessions; Table VIII reports a series of Wilcoxon signed-rank tests, run at the session level, on the experimental prices and their relationship to the theoretical predictions.[38]

[36] In a working paper, Cipriani, Fostel, and Houser (2012) describe the results of an experiment on the effect of collateralized borrowing on asset prices with an across-treatment design; in that experiment, they elicit subjects' demand and supply curves both in an economy where the risky asset can be used as collateral (Leverage Economy) and in an economy where it cannot (Nonleverage Economy). Consistent with the results described here, the price of the risky asset in the Leverage Economy is higher than its price in the Nonleverage Economy.

[37] The last four unpaid practice rounds were played using the same procedures as the paid rounds (two-asset economy with collateralized borrowing). For this reason, in Internet Appendix Section V, we report aggregate statistics combining the last four unpaid practice rounds and the 10 paid rounds. The results are in line with those reported here. Results for all unpaid practice rounds of the experiment are also reported separately in Internet Appendix Section VII.

[38] For each session, we compute the average prices of both assets and their spread. This yields for each variable a sample of seven observations. We test for price differences with a paired Wilcoxon

Table VIII

Nonparametric Wilcoxon Signed-Ranked Tests on Prices

This table reports the results of Wilcoxon signed-rank tests on the nulls that: (i) the average prices of the two assets are the same; and (ii) the average prices and the average spread equal the model's theoretical predictions.

H_0	H_1	p-Value
$P_Y = P_Z$	$P_Y > P_Z$	0.008
$P_Y = 277$	$P_Y \neq 277$	0.219
$P_Z = 218$	$P_Z \neq 218$	0.375
$P_Y - P_Z = 59$	$P_Y - P_Z \neq 59$	0.109

Table IX

Average Within-Round Standard Deviations of Asset Prices

This table reports the average within-round standard deviations of asset prices, computed across all paid rounds of all sessions and by session.

	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

The average trade price of Y is 268, whereas that of Z is only 224. These numbers are in line with their theoretical counterparts (277 for Y and 218 for Z), and the differences between the data and the theoretical predictions are not significant (with p-values equal to 0.219 and 0.375). We obtain similar results when we consider the median price in each round instead of the average price.[39]

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.[40] As Table VIII shows, such differences in prices are statistically significant (p-value = 0.008); moreover, they are robust to both session and round effects.[41] 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 the price of Z is 45, slightly lower than its theoretical counterpart of 59 (the difference is not significant, with a p-value of 0.109).

As Table IX shows, the average within-round standard deviation of transaction prices is relatively low: 6 for asset Y and 7 for asset Z. Furthermore, there is no evidence that prices have any trend within each round's trading time. Figure 1 shows the average prices of assets Y (solid line) and Z (dashed

signed-rank test; and for equality of prices and spread to their theoretical counterparts with single-sample Wilcoxon signed-rank tests. We run the tests on session averages to take into account any possible dependency among subjects' behavior within sessions.

[39] See Internet Appendix Section IV.

[40] Internet Appendix Section VI shows the per-round statistics.

[41] In Internet Appendix Section VIII.A, we run a panel data regression of average round prices controlling for round and session effects; consistent with the results of the nonparametric test, the regression results show that the price of asset Y is significantly higher than that of asset Z.

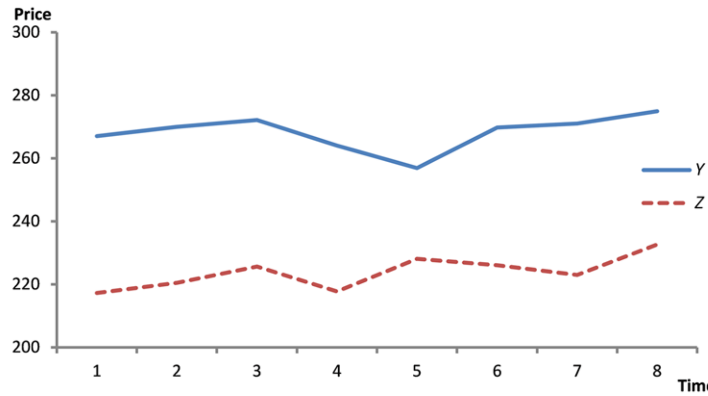

Figure 1. Asset prices over time within rounds. This figure displays the mean prices of assets Y and Z within each 20-second interval of the trading round. Each point on the graph shows the average for that time interval, across all paid rounds of all sessions. (Color figure can be viewed at wileyonlinelibrary.com)

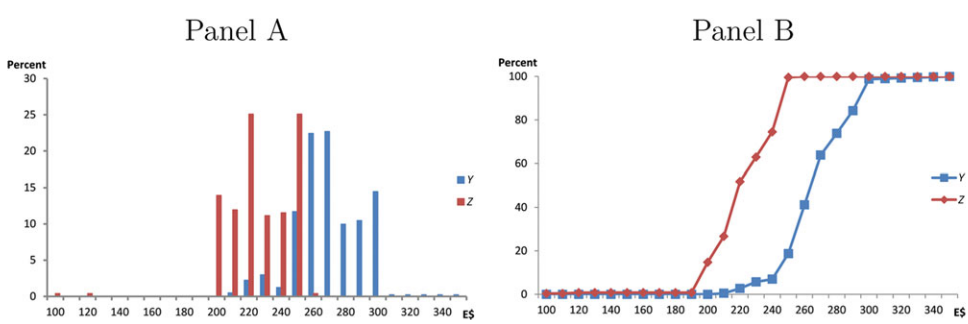

Figure 2. Histogram and cumulative histogram of asset prices. This figure displays the histogram (Panel A) and cumulative histogram (Panel B) of transaction prices for assets Y and Z, across all paid rounds of all sessions. (Color figure can be viewed at wileyonlinelibrary.com)

line) across rounds and sessions, computed separately for each of the eight 20-second intervals of the trading round.[42] As the figure shows, the prices of both assets Y and Z are stable within rounds.

Finally, Figure 2 displays the histogram and the cumulative histogram of transaction prices across rounds and sessions. The mass of the distribution of the price of asset Z is to the left of that of asset Y. The cumulative histogram shows that the sample distribution of transaction prices of Z first-order stochastically dominates that of asset Y. Indeed, across all sessions, in 89% of rounds, the minimum transaction price of asset Y is greater than the maximum transaction price of asset Z.

[42] The length of each trading round was 160 seconds.

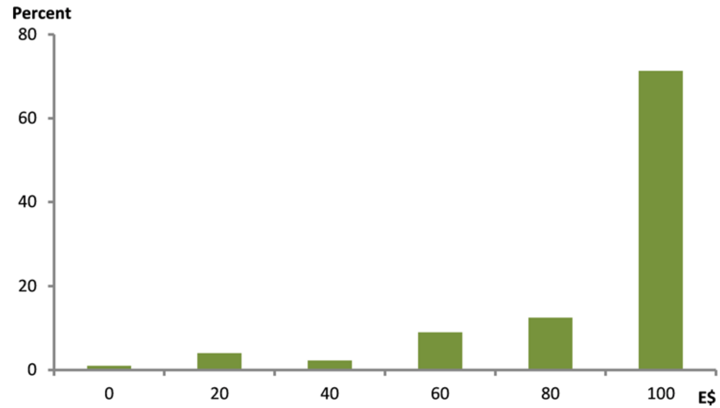

Figure 3. Histogram of borrowing per unit of asset Y. This figure displays the histogram of the amount borrowed in asset Y transactions, across all paid rounds of all sessions. (Color figure can be viewed at wileyonlinelibrary.com)

C. Borrowing, Cash, and Collateral Value

The spread between asset prices observed in the laboratory is consistent with the predictions of the theoretical model. In this section, we study the extent to which the spread is also generated by the same theoretical mechanism.

In our theoretical model, the deviation from the Law of One Price arises because Buyers need collateral to borrow: since Buyers are constrained and only asset Y can be used as collateral, they are willing to pay more for it than they are for asset Z. Indeed, in equilibrium, Buyers end up with zero cash holdings and leverage asset Y to the maximum (100). For this reason, we first look at Buyers' borrowing and final cash holdings in the laboratory. As Table X shows, Buyers' average borrowing per transaction is 86 and their median borrowing per transaction is 100, identical to its theoretical counterpart. More importantly, as the histogram in Figure 3 and the cumulative distribution in Table XI show, in approximately 70% of transactions Buyers borrowed the maximum per transaction (100); in 88% of transactions Buyers borrowed at least 60 (above half of the collateral capacity of the asset).

Table XII reports average and median final cash holdings across all Buyers, rounds, and sessions.[43] Average cash holdings are 106 and are relatively stable across sessions. Note that this is different from the value predicted by the theory (zero); nevertheless, since the average price of asset Y is 268 and that of asset Z is 224, at these average prices Buyers' average final cash holdings are not enough to buy any more assets (even if they borrowed 100 on a purchase of asset Y).

An average borrowing of 86 and an average final cash holding of 106 do not necessarily imply a departure from the theoretical mechanism generating

[43] Sellers' final cash holdings, which can be inferred from Buyers' final cash holdings and borrowing, are reported for completeness in Internet Appendix IV.

Table X

Borrowing per Unit of Asset Y

This table reports the mean, median, and standard deviation of the amount borrowed per unit of asset Y, across all paid rounds of all sessions and by session.

	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

Table XI

Proportion of Y Transactions Where Buyers Borrowed at Least a Given Amount

This table reports the proportion of asset Y transactions for which the Buyer borrowed at least a given amount, computed across all paid rounds of all sessions.

E$	1	20	40	60	80	100
Proportion	0.99	0.97	0.93	0.88	0.73	0.70

the spread between asset prices (that is, borrowing-constrained Buyers pay a higher price for Y because they need collateral). The reason is that, in the laboratory, assets 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 be unable to purchase additional units of assets Y or Z at their prevailing prices.

For this reason, we study the extent to which Buyers were constrained in the laboratory by looking at Buyers' borrowing and cash holdings jointly and by explicitly taking into account that subjects in the laboratory could not buy fractions of an asset. The first row of Table XIII reports the average proportion of Buyers who were unconstrained in terms of both cash holdings and borrowing at the end of the round. Buyers were unconstrained when their final cash holdings plus any unused borrowing capacity were greater than or equal to the cost of buying an additional asset. We define unused borrowing capacity as the difference between how much a Buyer could have borrowed given his/her holdings of Y (holdings of Y times 100) and how much (s)he actually borrowed. We define the cost of buying an additional asset as the minimum between the average price of asset Z in the round and the average down payment for Y in the round (the average price of asset Y minus 100).[44]

Table XIII shows that, on average, only 18% of Buyers were unconstrained at the end of the round, that is, in each round, on average, of the six Buyers, approximately one could have bought more assets than he actually did. Moreover, as the second and third rows of the table show, the median Buyer was unconstrained only in one round out of 10, and 17% of Buyers or less were

[44] Note that we take the minimum between p_Z and $p_Y - 100$ only in those rounds in which the Sellers have some units of asset Y left to sell at the end of the round; in the other rounds, we consider just the average price of Z.

Table XII

Buyers' Cash Holdings

This table reports the mean, median, and standard deviation of final cash holdings for Buyers, computed across all paid rounds of all sessions and by session.

	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

Table XIII

Unconstrained Buyers

The first row of this table reports, across all paid rounds and sessions, the average proportion of Buyers who were unconstrained at the end of the round, that is, Buyers whose final cash holdings plus unused borrowing capacity (defined as holdings of Y times 100 minus total borrowing) were 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 units of Y left at the end of the round) in that round. The average proportion is computed as the proportion of Buyer-round pairs. The second row of the table reports summary statistics for the number of rounds in which a Buyer was unconstrained. The third row of the table reports summary statistics for the proportion of Buyers that were unconstrained in each round.

	Average	P10	P25	Median	P75	P90
Proportion	0.18					
Number of Rounds per Buyer		0	0	1	3	5
Proportion of Buyers per Round		0.00	0.00	0.17	0.33	0.44

unconstrained in half of the rounds. 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 a deviation from the Law of One Price in the theoretical model.[45]

It is also interesting to study whether Buyers paid for collateral (by purchasing asset Y at a spread over asset Z) only when it was valuable to them. In the theoretical model, collateral is valuable (and Buyers are willing to pay more for asset Y) if and only if Buyers are borrowing constrained. This is not necessarily the case in the laboratory because of asset indivisibility. For instance, consider a Buyer facing a price of 250 for asset Y and 200 for asset Z. If the Buyer has 190 in cash, he cannot buy asset Z and needs to borrow only 60 to buy asset Y; although the subject is not borrowing constrained, borrowing is still valuable to him since it allows him to increase his holdings of the risky asset. Therefore, it is rational for the Buyer to pay more for asset Y, even if he is not borrowing the maximum. In contrast, if the Buyer has 200 in cash, he

[45] Internet Appendix Section 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 do not change in a meaningful way.

Table XIV
Buyers Who Paid for Collateral Capacity without Using It

The first row of this table reports, across all paid rounds and sessions, the average proportion of Buyers who paid for collateral capacity without using it, that is, Buyers holding at least one unit of asset Y at the end of the round who paid more for it than the average price of Z in the round, and whose down payment on Y plus additional cash holdings was greater than or equal to the average price of asset Z; for Buyers who purchased more than one unit of Y, we consider the last unit bought. The average proportion is computed as the proportion of Buyer-round pairs. The second row of the table shows summary statistics for the number of rounds in which a Buyer paid for collateral capacity without using it. The third row of the table shows summary statistics for the proportion of Buyers who paid for collateral capacity without using it in each round.

	Average	P10	P25	Median	P75	P90
Proportion	0.25					
Number of Rounds per Buyer		0	1	2	4	5
Proportion of Buyers per Round		0.00	0.17	0.17	0.33	0.50

can buy asset Z; if instead the Buyer purchases asset Y at a higher price, he pays a positive price for collateral without needing it. In Table XIV, we study how often this happened; that is, how often Buyers paid more for asset Y than for asset Z without needing collateral. The first row of Table XIV reports the average proportion of Buyers who paid for collateral capacity without needing it.[46] These are 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 down payment for that unit plus any final cash holdings was greater than or equal to the average price of asset Z.[47] As the table shows, on average 25% of Buyers in each round paid for collateral capacity without needing it. Moreover, as the second and third rows of the table show, the median Buyer could have afforded buying her/his own asset allocation without borrowing in two rounds out of 10; additionally, in the median round, 17% of Buyers paid for collateral capacity without using it.[48]

In summary, the results of Tables XIII and XIV 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.

[46] This could be thought of as a rationality test in the tradition of Afriat's revealed preference tests.

[47] For Buyers who bought more than one unit of asset Y, we only consider the last unit bought (the marginal unit).

[48] Internet Appendix Section IX reports the results of a robustness check on the same statistics, where (i) instead of using mean round prices, we use the quotes that Buyers were facing; and (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 XV

Buyers' Final Holdings of Assets Y and Z

This table reports the mean, median, and standard deviation of end-of-round Buyers' holdings of assets Y (Panel A) and Z (Panel B), across all paid rounds of all sessions and by session.

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	0.90	0.93	0.95
Median	1	1	1	1	1	1	1	1
SD	0.74	0.71	0.76	0.86	0.90	0.66	0.61	0.67
Panel B: Buyers' Final 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	0.50
Median	1	1	1	0	1	1	1	0.5
SD	0.52	0.55	0.50	0.50	0.50	0.46	0.58	0.50

Table XVI

Nonparametric Wilcoxon Signed-Rank Tests on Holdings

This table reports the p-values for a series of Wilcoxon signed-rank tests: (i) Buyers' final holdings of asset Y (Y^B) are greater than Sellers' (Y^S); (ii) Buyers' final holdings of asset Z (Z^B) are smaller than Sellers' (Z^S); (iii) Buyers' final holdings of asset Y (Y^B) are greater than those of asset Z (Z^B); and (iv) Sellers' final holdings of asset Y (Y^S) are smaller than those of asset Z (Z^S).

Variable	H_0	H_1	p-Value
Y Holdings	$Y^B = Y^S$	$Y^B > Y^S$	0.008
Z Holdings	$Z^B = Z^S$	$Z^B < Z^S$	0.008
Buyers' Holdings	$Y^B = Z^B$	$Y^B > Z^B$	0.008
Sellers' Holdings	$Y^S = Z^S$	$Y^S < Z^S$	0.008

D. Asset Allocation

Table XV reports the average final asset holdings per Buyer;[49,50] Table XVI reports a series of nonparametric Wilcoxon signed-rank tests on final asset holdings.[51] As in the theory, Buyers hold almost all the supply of the collateralizable asset Y: the average Buyer's holdings of Y are 0.91 and the median is 1, equal to its theoretical counterpart. Buyers' holdings of asset Y are larger than Sellers' holdings of Y. As Table XVI shows, the difference in holdings is statistically significant (p-value $= 0.008$) and robust to both session and round

[49] Sellers' final holdings are given by the overall asset supply minus Buyers' asset allocations. We report them in Internet Appendix Section IV for completeness.

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

[51] The tests are computed similarly to the tests on prices described in Footnote 38.

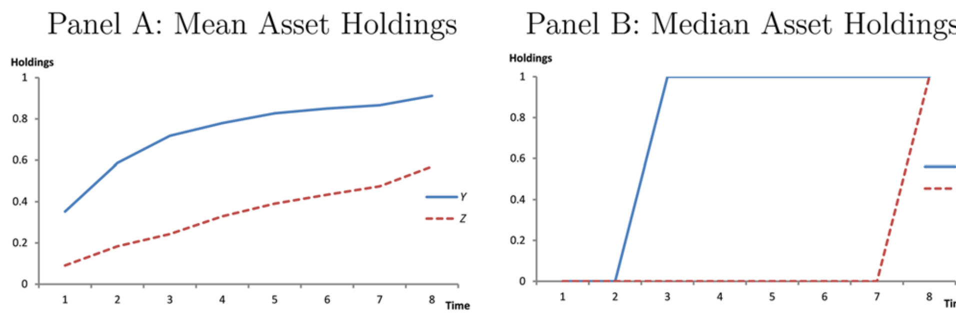

Figure 4. Buyers' asset holdings over time within rounds. This figure displays the mean and median (Panels A and B) Buyers' holdings of assets Y and Z within each 20-second interval of a trading round. Each point on a graph shows the average or median for that time interval across all paid rounds of all sessions. (Color figure can be viewed at wileyonlinelibrary.com)

effects.[52] Although the median Buyer's holdings of Z are also equal to their theoretical counterpart of 1, the average is only 0.57, reflecting the fact that some Buyers only bought asset Y. Indeed, Buyers' holdings of Y are higher than those of Z, a statistically significant difference (p-value $= 0.008$), and robust to both session and round effects. As in our theoretical model, since Buyers did not purchase all the risky asset supply, the final allocation in the laboratory is not Pareto efficient. Moreover, since on average fewer risky assets changed hands from Sellers to Buyers than theory predicts, more gains from trade are left unexploited in the laboratory than in the theoretical model.

We can gain further insight into how the market allocates the risky assets by looking at the evolution of holdings within rounds. In Figure 4, we show the average and median Buyer's holdings of assets Y (solid line) and Z (dashed line) across all paid rounds of all sessions, computed separately for each of the eight 20-second intervals of a trading round.[53] As the figure shows, in each interval in the round, Buyers hold a larger proportion of Y than of Z; these differences between Buyers' holdings of Y and Z are statistically significant (see Internet Appendix Section VIII.B). This result suggests that Buyers obtained asset Y earlier in the round because they wanted to exploit its collateral capacity; only at the end of the round they bought asset Z, using leftover cash to buy the cheaper asset.

E. Convergence to Collateral Equilibrium

In this section, we study whether asset prices, borrowing, and final holdings converge toward the collateral equilibrium as subjects become more

[52] In Internet Appendix Section VIII.A, we run a panel regression on average final holdings, controlling for round and session effects. We mirror the nonparametric tests of Table XVI through a series of F-tests reported in Table IA.XXX; the results are aligned with those of the nonparametric tests.

[53] The length of each trading round was 160 seconds.

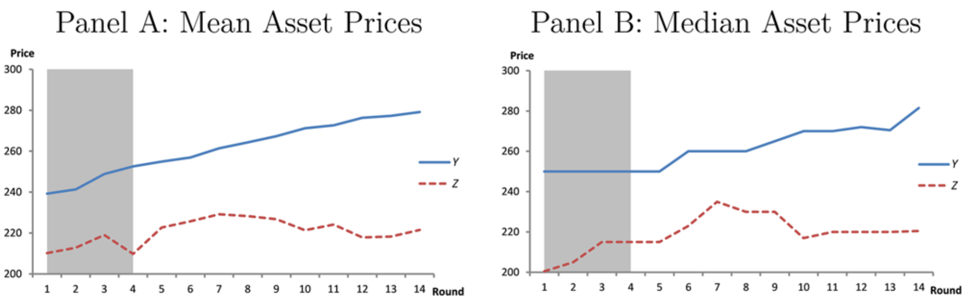

Figure 5. Asset prices over rounds. This figure displays the mean and median (Panels A and B) transaction prices of assets Y and Z in each of the last four unpaid practice rounds (shaded) and the 10 paid rounds of the experiment across all sessions. (Color figure can be viewed at wileyonlinelibrary.com)

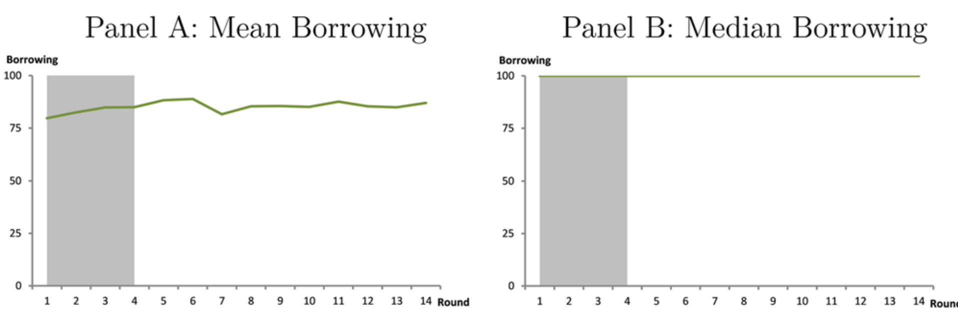

Figure 6. Borrowing per asset Y over rounds. This figure displays the mean and median (Panels A and B) amount borrowed per traded asset Y in each of the last four unpaid practice rounds (shaded) and the 10 paid rounds of the experiment across all sessions. (Color figure can be viewed at wileyonlinelibrary.com)

experienced in trading. To this end, we study how these variables evolved over the trading rounds, considering both the last four unpaid practice rounds (which used the same procedures as in the paid rounds) and the 10 paid rounds of the actual experiment.

In Figures 5 to 8, we display average and median (Panel A/Panel B) prices (Figure 5), borrowing per unit of asset Y (Figure 6), Buyers' asset holdings (Figure 7), and the proportion of unconstrained Buyers (Figure 8),[54] computed separately for each round of trading; the figures report information on both the last four unpaid practice rounds (shaded) and on the 10 paid rounds. In Table XVII, we report the mean of the same variables computed separately for the last four unpaid practice rounds, for the first four paid rounds, and for the last four paid rounds; in Table XVIII, we report the p-values of Wilcoxon signed-rank tests on their differences.

Figure 6 shows that borrowing per unit of asset Y is stable across rounds and close to the prediction of the theoretical model from the very first rounds.

[54] The proportion of unconstrained Buyers is computed using the same approach as in Table XIII.

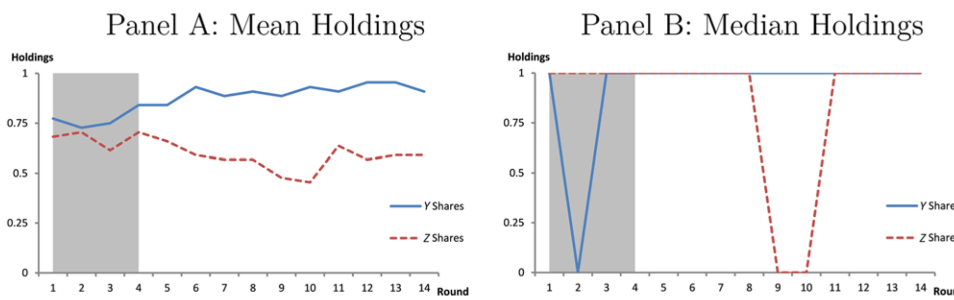

Figure 7. Buyers' asset holdings over rounds. This figure displays the mean and median (Panels A and B) Buyers' holdings of assets Y and Z in each of the last four unpaid practice rounds (shaded) and the 10 paid rounds of the experiment across all sessions. (Color figure can be viewed at wileyonlinelibrary.com)

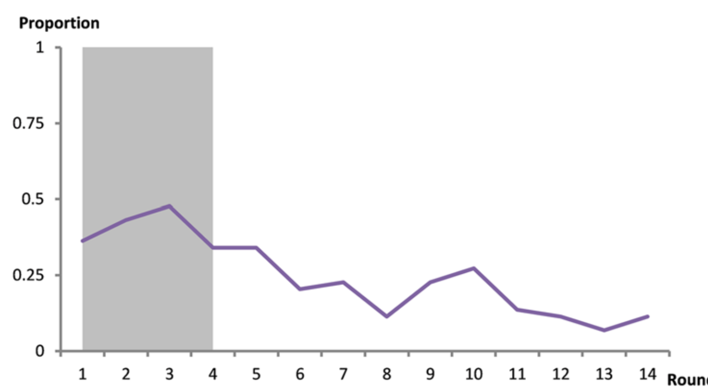

Figure 8. Proportion of Unconstrained Buyers by Round. This figure displays the average proportion of Buyers in each round that are unconstrained, as defined in Table XIII, in each of the last four unpaid practice rounds (shaded) and the 10 paid rounds of the experiment across all sessions. (Color figure can be viewed at wileyonlinelibrary.com)

In particular, average borrowing per asset is 83 in the practice rounds and increases only slightly toward the end of the experiment to 86, a statistically insignificant difference (p-value $= 0.938$). Thus, from the very beginning of the experiment (even in the practice rounds), Buyers understood that borrowing was valuable as it allowed them to purchase more units of the risky assets; as a result, they exploited (almost) all of asset Y's collateral capacity.

Consistent with the fact that Buyers value borrowing, from the very beginning of the experiment (even in the practice rounds), there is a positive spread between the average prices of asset Y and Z (246 and 213), a statistically significant difference (p-value $= 0.016$).[55] However, unlike the behavior of borrowing, the average spread between the prices of assets Y and Z increases over

[55] Statistics on the last four unpaid practice rounds are reported in Internet Appendix Section VII.C.

Table XVII

Convergence to Collateral Equilibrium across Rounds

The table reports means of the price of asset Y, the price of asset Z, the spread between the two, the amount borrowed per unit of asset Y, the end-of-round Buyers' holdings of assets Z and Y, and the proportion of unconstrained Buyers (computed as in Table XIII), computed separately for the last four unpaid practice rounds, for the first four paid rounds, and for the last four paid rounds of the experiment.

Variable	Last Four Unpaid Practice Rounds	First Four Paid Rounds	Last Four Paid Rounds
P_Y	246	259	276
P_Z	213	226	221
$P_Y - P_Z$	33	33	56
Borrowing	83	86	86
Buyer Holdings of Y	0.77	0.89	0.93
Buyer Holdings of Z	0.68	0.60	0.60
Proportion of Unconstrained Buyers	0.40	0.22	0.11

Table XVIII

Nonparametric Wilcoxon Signed-Rank Tests

The table reports p-values for a series of Wilcoxon signed-rank tests of the null hypotheses that the mean asset prices, spread, borrowing, holdings, and proportion of unconstrained Buyers are the same: (i) in the last four unpaid practice rounds (E) and the last four paid rounds (L); and (ii) in the first (E) and last (L) four paid rounds.

	H_0	H_1	Last Four Unpaid Practice Rounds	First Four Paid Rounds
P_Y	$P_Y^E = P_Y^L$	$P_Y^E < P_Y^L$	0.016	0.016
P_Z	$P_Z^E = P_Z^L$	$P_Z^E < P_Z^L$	0.055	0.148
Spread	$S^E = S^L$	$S^E \neq S^L$	0.031	0.016
Borrowing	$B^E = B^L$	$B^E \neq B^L$	0.938	0.813
Buyers' Holdings Y	$Y^E = Y^L$	$Y^E \neq Y^L$	0.031	0.469
Buyers' Holdings Z	$Z^E = Z^L$	$Z^E \neq Z^L$	0.313	0.984
Proportion of Unconstrained Buyers	$U^E = U^L$	$U^E \neq U^L$	0.031	0.172

the experimental rounds, from 33 in the practice rounds to 56 in the last four paid rounds, a statistically significant difference (p-value = 0.031). Whereas the average price of asset Z is relatively stable across rounds (213 in the practice rounds and 221 in the last four paid rounds of the experiment), there is a clear upward trend in the price of the collateralizable asset Y, from 246 in the practice rounds to 276 in the last four paid rounds, a statistically significant difference (p-value = 0.016); see Figure 5. Thus, starting from the very first rounds, Buyers valued borrowing and as a result were willing to pay more for asset Y than for asset Z; as the experiment progressed, their valuation of asset Y's collateral capacity increased, converging toward the theoretical prediction.

Moreover, as Buyers discovered the value of asset Y over the course of the experiment, they not only were willing to pay more for it, but also bought more units of it (see Figure 7). Indeed, Buyers' final holdings of asset Y increase from 0.77 in the practice rounds to 0.93 in the last four paid rounds, a statistically significant difference (p-value $= 0.031$). Since as the experiment progressed, Buyers bought more units of asset Y at a higher price, fewer of them were unconstrained at the end of the round; indeed, as Figure 8 and Tables XVII and XVIII show, the proportion of unconstrained Buyers decreases over the course of the experiment, from 40% in the practice rounds to 11% in the last four paid rounds of the experiment, a statistically significant difference (p-value $= 0.031$).

E.1. Deviations from the Law of One Price and Convergence to Collateral Equilibrium

In the laboratory, a spread between the prices of assets Y and Z emerges from the very beginning and widens as the experiment progresses, getting closer and closer to the theoretical prediction. Narrower spreads in earlier rounds may reflect subjects' attempts to arbitrage away the price differences (which are not real arbitrage opportunities due to the collateral constraint); one may expect that, as convergence occurs, these attempts become fewer and fewer. We show that this is indeed the case.

In the first row of Panel A in Table XIX, we report the proportion of times when a Buyer purchased asset Y by accepting an existing Sell Offer even though a Sell Offer for asset Z was available at a lower price,[56] that is, the proportion of times a Buyer refrained from arbitraging away the price spread. We report this proportion separately for the last four unpaid practice rounds, for the first four paid rounds, and for the last four paid rounds of the experiment, along with the p-values of Wilcoxon signed-rank tests on their differences. As Table XIX shows, the proportion of times a Buyer refrained from arbitraging away the price spread increased from 50% in the practice rounds to 68% in the last four paid rounds of the experiment; the difference is significant at the 10% level (p-value $= 0.063$).[57] This suggests that, over the rounds, Buyers learn that a difference in prices between asset Y and asset Z does not represent a real arbitrage opportunity, but reflects the collateral value of asset Y in an economy in which agents are borrowing constrained.

[56] As we explain in Section II, a transaction occurs either when a Buyer posts a Buy Offer that crosses an existing Sell Offer and is immediately executed, or when a Seller posts a Sell Offer that crosses an existing Buy Offer and is immediately executed. The first type of transactions are Buyer-initiated, the second type of transactions are Seller-initiated.

[57] As a robustness check, in the third and fourth rows of Panel A in Table XIX, we recompute the statistics focusing on Buy Offers posted when the spread between the prices of assets Y and Z was lower than 59, the spread predicted by the theoretical model; that is, we excluded those circumstances in which the spread was so large that, according to the model, a Buyer should have bought asset Z. The results are very similar.

Table XIX

Deviations from the Law of One Price and Convergence to Collateral Equilibrium

Panel A reports the proportion of Buyer-initiated transactions (the Buyer accepted an existing Sell Offer) in the last four unpaid practice rounds, in the first four paid rounds, and in the last four paid rounds in which: (1) there was a Sell Offer for both assets and $P_Z < P_Y$; and (2) there was a Sell Offer for both assets and $0 < P_Y - P_Z < 59$. Panel B reports (1) the proportion of all Buy Offers for asset Y that do not immediately match an existing Sell Offer for Y and there was a Sell Offer for asset Z at the time of the offer and $P_Z < P_Y$; and (2) the proportion of all Buy Offers for asset Y that were later matched, and there was a Sell Offer for asset Z at the time of the offer and $P_Z < P_Y$. The table also reports Wilcoxon signed-rank test p-values for tests of the equality of the proportions: (i) in the last four unpaid practice rounds versus the last four paid rounds; (ii) in the first four paid rounds versus the last four paid rounds.

	Last Four Unpaid Practice Rounds	First Four Paid Rounds	Last Four Paid Rounds
Panel A: Sell Offers Accepted			
$P_Z < P_Y$	0.50	0.66	0.68
p-Value	0.063	0.938	
$0 < P_Y - P_Z < 59$	0.52	0.64	0.67
p-Value	0.063	0.313	
Panel B: Buy Offers Posted			
$P_Z < P_Y$ (not matched)	0.26	0.48	0.73
p-Value	0.016	0.031	
$P_Z < P_Y$ (matched later)	0.53	0.79	1.00
p-Value	0.031	0.063	

Buyers' increasing willingness to pay more for asset Y over the course of the experiment can also be observed by looking at their posted Buy Offers that were not immediately executed. Panel B in Table XIX reports the proportion of times Buyers post a Buy Offer for asset Y at a higher price than an existing Buy Offer for asset Z. In the practice rounds, this happens only 26% of the time, whereas in the last four paid rounds it happens 73% of the time, a statistically significant difference (p-value = 0.016). In other words, both if we look at Buyers' behavior when they accept Sellers' Sell Offers and when they post Buy Offers that remain in the order book, we observe that, as the experiment progressed, Buyers became more willing to pay a spread to purchase the collateralizeable asset.

IV. Conclusion

This is the first paper to study, in a controlled laboratory environment, how collateralized borrowing creates 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 assets with identical payoffs but different collateral capacities; the asset that can be used as collateral fetches higher prices than the asset that cannot.

In the laboratory financial market, subjects trade the two assets in a double auction. The two assets have identical payoffs, thereby allowing us to directly test for the presence of collateral value and for deviations from the Law of One Price. In the laboratory, the asset that can be used as collateral fetches a higher price, as the theory predicts. The spread between collateralizeable and noncollateralizeable assets is significant. Most importantly, the spread stems from the fact that most of the subjects are constrained and hence are willing to pay for collateral—the same mechanism highlighted by the theory. Although a spread between the two assets emerges from the first rounds of trading, its size increases as the experiment progresses, becoming closer and closer to its theoretical counterpart. Finally, as subjects discover the value of collateral, they become increasingly less willing to trade on deviations from the Law of One Price as they understand that such deviations do not represent real arbitrage opportunities.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's website:

Appendix S1: Internet Appendix.
Replication Code.