Market frictions and the anatomy of an arbitrage

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December 8, 2017

Under standard models of asset markets persistent arbitrage opportunities can only exist when market frictions, such as limited short sales and restricted leverage, constrain traders' capacities to exploit and compete away these opportunities. We show in a series of laboratory markets for a single asset, for which there is symmetric information and certain fundamental value, eliminating these frictions does not drive out frequent arbitrage opportunities. Baseline experiments forbid short sales and leveraged purchases, and we observe significant arbitrage involving both over- and under-pricing of the asset. When we introduce generous short-sell capacities, arbitrage opportunities involving over-pricing are largely eliminated, but those involving under-pricing not. In contrast, when we only add generous capacities for leveraged purchases, under-pricing arbitrage opportunities are largely eliminated, but those involving over-pricing not. Surprisingly, when we introduce both the short-sale and leveraged purchase facilities the presence of arbitrage opportunities, both from over- and under-pricing, returns to the baseline levels.

We discover arbitrage opportunities are greatly reduced when we increase the market size of the baseline in two ways. First, we increase the number of market participants by 150%, keeping the same individual levels of endowments of asset units and cash, and arbitrage is greatly reduced. Second, we hold the number of market participants constant but increase each of their endowments by 150%, and arbitrage is also largely eliminated. This study provides evidence that arbitrage opportunities are eliminated, and correspondingly asset markets are more price efficient, not by relaxing market frictions but rather through by increasing capitalization while maintaining frictions.

Keywords: Limits of arbitrage, Experimental asset markets, Market capitilization

JEL Classification Numbers: C92, D53, G12

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1 Introduction

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According to rational expectations theory, a suitable equilibrium concept would require traders' models used to form their expectations not be obviously controverted by their observations if traders have any opportunity to compare the results of the operation of the market with their own models (Radner, 1979). In efficient markets, the equilibrium price of an asset should converge to the sum of its discounted rationally expected dividends in the future, and price changes only when information that affects traders expectations arises. If price deviate from fundamental value, the potential profit which could be earned from the difference between price and fundamental value would generate nonzero excess demand for assets, and these arbitrages conducted by traders would bring asset price back to fundamental value and keep price efficient.

However, some empirical evidence shows that arbitrage fails to drive the price to fundamental value in asset markets, which contradicts efficient market hypothesis. The anomalies include price overreaction, short-run positive autocorrelation and longer-term negative autocorrelation, the closed-end fund puzzle, and the glamour-value anomaly and etc. For instance, De Bondt and Thaler (1985) used CRSP monthly return data to test the efficiency of asset market. They found that (1) Extreme movements in stock prices will be followed by subsequent price movements in the opposite direction. (2) The more extreme the initial price movement, the greater will be the subsequent adjustment. Both of their findings imply a violation of market efficiency.

In the real asset markets, we do not know the fundamental value (fv) of the asset, so we have to impose some assumptions on the dynamics of fv to test whether there exists arbitrage opportunities or not. Therefore, we utilize laboratory asset markets to test the limits of arbitrage, where we can control the dividend distribution, and traders' knowledge of it in a market with finite trading horizon (Smith et al., 1988). In our experiment, we design a novel dividend process, sampling without replacement, which has unique rational

expectation equilibrium regardless of risk attitude, so any price deviation from fv would amount to risk free arbitrage. And, the probabilistic nature of fundamental dynamics is fully explained to traders.

To begin with, we run several baseline sessions where traders face liquidity and short sale constraints. We do observe that 1) persistent arbitrage does exist in markets; 2) some traders go to corner solutions of cash and asset. Since we find that arbitrage fails to bring price to fundamental value, then we test the commonly cited reasons for limits of arbitrage.

Actually, some theoretical papers worked on explaining the limits of arbitrage which is inconsistent with efficient market hypothesis. De Long et al. (1990) holds that insufficient liquidity causes the persistent arbitrage. The unpredictability of noise traders beliefs creates a risk in the price of the asset that deters rational arbitrageurs from aggressively betting against them. If the arbitrageur has to liquidate before the price recovers, he suffers a loss. Fear of this loss should limit his original arbitrage position. And, Shleifer and Vishny (1995) also found that in some circumstance where price does not converge to fundamental value in the short run, arbitrageur does not make money with probability one, and may need substantial amounts of capital to both execute his trades and cover his losses. When arbitrage requires capital, arbitrageurs can become most constrained when they have the best opportunities, i.e. when the mispricing they have bet against get even worse. The fear of this scenario would make them more cautious when they put on their initial trades.

Both our observations in baseline sessions and the conclusions draw by theoretical papers admit the possibility that eliminating market frictions may diminish arbitrage, so we remove liquidity constraints, short sale constraints or both in other three treatments respectively. Moreover, we conduct competition treatment by substantially increasing the number of traders in each session while maintaining liquidity and short sale constraints.

The data analysis indicates that elimination of market frictions does not diminish arbitrage or improve price efficiency, which contradicts the theoretical predictions in the existing literature. However, competition decreases arbitrage significantly and results in most price

efficient among all treatments. Our explanation is that in the liquidity treatment traders have more cash to bid up gradually to maximize profit, but not enough people compete in the bid queue. Other treatments have similar situation. Moreover, we find that in competition treatment traders are more likely go to the corner solutions, that is, in competition sessions the portion of traders who run out of money or asset at the end of the period are significantly higher than that in other sessions.

2 Experimental design

2.1 Assets, dividends and arbitrage

Consider a world with two commodities. One is a non-interest bearing and non-dividend paying commodity called "pesos," whose units we express in ₱. The second is an asset that lives for five periods, pays a peso dividend each at the conclusion of each period, observable to all, and a commonly known terminal redemption of ₱21. The sequence of the asset's dividends is determined by randomly selecting **without replacement** from the following set of values: $\{-6, -6, -6, 6, 6\}$. At any point in time, if we know the past realizations of dividends, we know with certainty the value of the sum of the remaining dividends and the terminal redemption value. Consequently, as long as we only value the closing balance of pesos after terminal redemptions[1], the asset always has a known and certain peso equivalent. This peso equivalent is the fundamental value of the asset.

What is arbitrage in this world? When there is an exchange of a unit of the asset for an amount of pesos which differs from the fundamental value, an arbitrage has occurred. If the amount of pesos is below the fundamental value, we call it a buy arbitrage; the buyer has ensured herself a certain gain in her final pesos holdings. Consider an example. Suppose it is period two and the period one dividend was ₱6. The fundamental value of the asset is

[1] Or alternatively we don't discount the stream of dividends, are indifferent over the sequence by which the future dividends are realized, or have non-Bayesian subjective beliefs about when a remaining dividend value will be drawn.

now ₱9. If a trader purchases a unit of the asset at a price of ₱4, this buyer's final pesos holdings will increase by ₱5 assuredly assuming she holds the asset until the redemption.

When there is an exchange of a unit of the asset for an amount of pesos which is above the fundamental value, we call it a sell arbitrage. Consider another example. Suppose it is period four and the previous three dividends were ₱6, ₱-6, and ₱6. The fundamental value of the asset is now ₱9. If a trader sells a unit of the asset at a price of ₱14, this seller would assuredly increase her final pesos holdings by ₱5.

2.2 Market microstructure

We now specify the continuous double auction within which trades of pesos and asset units occur. Each period, prior to the dividend realization, there is a fixed length of time in which traders may generate publicly observable messages which can lead to bilateral trades. There are four types of messages traders can submit. The first two are limit orders. A limit bid is an amount of pesos at which the trader is willing to purchase a unit of the asset. A limit ask is an amount of pesos a trader is willing to accept to provide a unit of the asset. These limit bids and asks are publicly displayed in the "order book." Limit bids are listed from highest to lowest, while limit asks are listed from the lowest to highest. The lowest limit ask and the highest limit bid define what is often called the bid-ask spread. We impose rules restricting the submission and removal of limit orders. Any new limit bid must exceed any limit bid in the order book, and any new limit ask must be lower than any other limit ask in the order book. A trader can freely withdraw a limit order from the order book as long as it is not the highest bid or lowest ask. We defer discussion of other restrictions that are conditional upon a trader's portfolio. A transaction occurs whenever a trader submits a limit bid above the current lowest limit ask, with the transaction price equal to the earlier submitted limit ask. Likewise, a transaction occurs whenever a trader submits a limit ask below the current highest limit bid, with the transaction price equal to the earlier submitted limit bid. We evacuate the order book when a trading period concludes.

There are two other types of messages a trader may submit: market buys and market sells. A trader submits a market buy when she wishes to purchase a unit at the lowest limit ask in the order book. This generates a transaction in which the trader who submits the market buy exchanges an amount of pesos equal to the lowest current ask for a unit of the asset from the trader who submitted that limit ask. Similarly, a trader submits a market sell when she wishes to sell a unit of the asset at the highest limit bid in the order book. This generates a transaction in which the trader who submits the market sell exchanges a unit of asset for an mount of pesos equal to the highest current ask from the trader who submitted that limit ask. Note that whenever a transaction occurs the involved limits order(s) are removed from the order book. We forbid traders from submitting market orders that transact with their own limit orders. We defer discussion of other restrictions that are conditional upon a trader's portfolio.

These rules define a continuous double auction, and allow for three types of arbitrage opportunities: explicit, implicit and unrealized. Each of these can manifest as either a buy or sell arbitrage. In an explicit arbitrage either a limit ask is submitted lower than the fundamental value and is accepted by a market buy or matched with a subsequent limit bid (explicit sell arbitrage), or a limit bid is submitted exceeding the fundamental value and is accepted by a market sell or matched with a subsequent limit ask (explicit buy arbitrage). When a limit ask is submitted which exceeds the fundamental value and is subsequently accepted, or when a limit bid is submitted below the fundamental value and is subsequently accepted, this is called implicit arbitrage. The former is an implicit sell arbitrage and the latter is an implicit buy arbitrage. Finally, when a limit ask is submitted below the fundamental value, or a limit bid is submitted above the fundamental value, but the trading period expires with the limit order still in the order book this is called an (buy or sell accordingly) unrealized arbitrage.

2.3 Endowments, feasible portfolios and market frictions

We complete the specification of the microeconomy by noting there are n traders each with a common portfolio endowment of pesos and units of the asset, $(\mathring{₱}, \mathring{A}) = (100, 3)$.[2] The specification of additional rules on limit and market orders define the sets of feasible commodities (i.e. portfolios) and, at the same time, market frictions. These market frictions are forms of short sale and leveraged purchase constraints.

We restrict limit asks and market sells conditional upon a trader's current holding of assets and her limits orders in the order book. These are short sale constraints. We define the short sale limit K as a lower bound on the number of assets held in a trader's portfolio less the number of limit asks she owns in the order book. When this difference reaches the lower bound K she can no longer submit any limit asks or market sell orders. When $K = 0$ there are no short sales permitted in the market. When we allow for short sales, we adopt an alternative level of $K = -235$. When the minimum possible fundamental value of the asset of three is realized, $K = -235$ is still sufficient for any one trader to absorb the aggregate endowment of pesos in the market. When a trader holds a negative quantity of the asset at the conclusion of a trading period they "pay" rather than receive the dividend for each negative unit. If they hold a negative quantity of the asset at the end of period 5, they must pay the terminal redemption for each short sold unit of the asset.

We also restrict limit bids and market buys conditional upon a trader's current peso holdings and her limit bids in the order book. These are leverage constraints. We define the leverage limit L as a lower bound on a trader's peso holdings less the total value of pesos she has committed to limit bids in the order book. When $L = 0$ there is no facility to borrow pesos from in order to purchase units of the asset. At times we provide a facility from which any trader can borrow pesos at an zero interest rate. In this case the alternative leverage limit is $L = -600$. At this limit any trader can purchase the entire aggregate endowment of the asset at its maximum possible fundamental value of ₱33. If a trader holds a negative

[2] The number of traders and the common endowment is public knowledge.

quantity of pesos after period 5, then she must pay this balance from her terminal redemption values of her final asset holdings.

We create the first of our two key experimental treatment designs by turning on and off the short sale and leveraged purchase constraints. When we impose short sale and leverage constraints, i.e. maximal market frictions, a trader's portfolio is approximately[3] constrained to the positive orthant of the Cartesian plane. This is depicted as region I in Figure 1, which includes the individual traders' common endowment $(\mathring{P}, \mathring{A}) = (100, 3)$. We call this our "Baseline" environment. When we allow for short sales the set of feasible portfolios approximately extends to include both regions I and II, where the short sale limit $K = -235$ is indicated by the horizontal dashed line. We call this our "Short sale" environment. When we allow for leveraged purchases, but no short sales, the feasible set of portfolios consists of regions I and III, where the vertical dashed line indicates the leverage limit $L = -600$. We call this our "Liquidity" environment. When we remove all market frictions, i.e. allow for both short sales and leveraged purchases, the set of feasible portfolios consist of regions I through IV. We call this our "Liquidity + Short sales" environment.

2.4 Capitalization

We create the second of our two key experimental treatment designs by varying the aggregate wealth of the two-good economy. We do this through the manipulation of the number of traders, n, or the size of the traders' portfolio endowments. In this experimental design we only utilize the Baseline environment, which prohibits short sales and leveraged purchases. First, we consider an economy with eight traders, $n = 8$, each with a portfolio endowment of $(\mathring{P}, \mathring{A}) = (100, 3)$. This serves as the Baseline treatment for both of our experimental designs. Next, we consider a 2.5 fold-replication of this baseline economy. In other words we enlarge the economy by including 2.5×8, or 20, traders each with the same portfolio endowment of

[3]When trader take a position with a large asset-to-peso ratio it is possible for her pesos holdings to become negative through the realization of negative valued dividends. In such cases, we don't force her to sell assets to comply with the non-negative pesos constraint but do forbid her from submitting limit bids and making market buys.

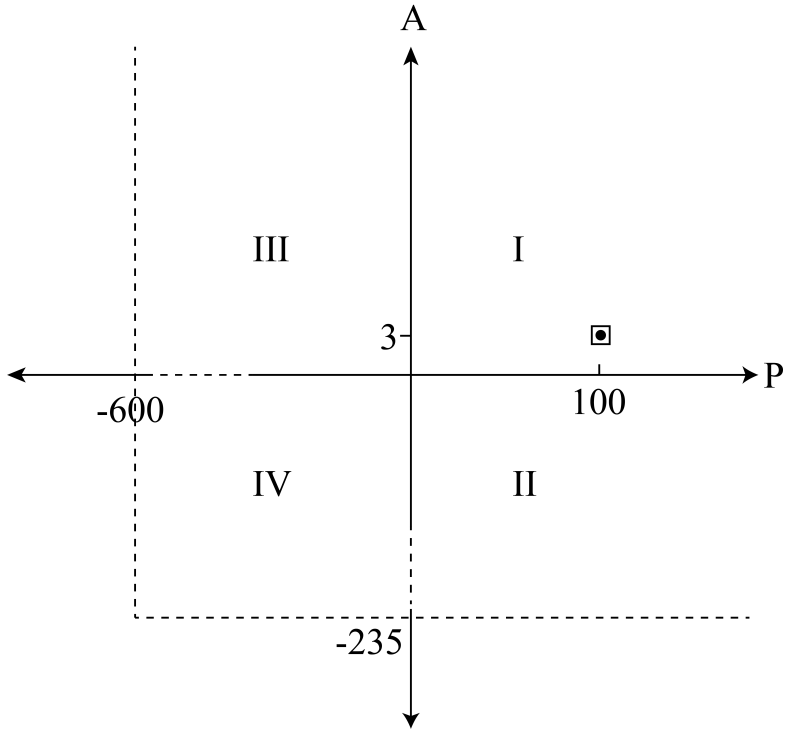

Figure 1: Feasible commodity spaces: the alternative sets of feasible portfolios as determined by alternative combinations of short sale and leverage constraints.

$(100, 3)$. This leads to a 150% increase in the aggregate wealth, from ₱1160 in the Baseline treatment to ₱2900, while maintaining a per capita initial wealth of ₱145. We call this our "Competition" treatment. Our other capitalization manipulation is to maintain $n = 8$ while increasing initial portfolio endowments so that aggregate wealth is ₱2900. This is achieved by giving four traders the portfolio endowment $(250, 7)$ and the other four traders $(250, 8)$. We call this our "Big endowment" treatment.

Here we present a two table with our experimental design. the first is a 2x2 matrix for short-sale leverage, in each cell put n=8, market endowment; the second table is 1x3 matrix, the column labels are Baseline, Competition and Big Endowment

2.5 Experimental procedures

We have a total of six experimental treatments: Baseline, Short sales, Liquidity, Liquidity + Short sales, Competition and Big endowment. We use a between subject design; each

experimental session experiences exactly one of the six treatments. For each treatment we conducted five sessions.

We start each experimental session by providing a detailed hard copy of the instructions[4] which we asked them to read quietly along with a monitor who read them aloud. This establishes public mutual knowledge regarding all aspects of the experimental session. After reading the instructions, we required traders to privately and correctly answer at least nine out of ten questions to demonstrate their adequate understanding of the dividend structure, how experimental earnings were determined and the trading rules. At this point we initiated a sequence of five independent markets, each lasting five periods. We paid the traders for only one of the five markets. At the conclusion final market, the monitor rotated a bingo cage and selected randomly from the five balls to determine which market we would use to determine the traders' earnings. Traders were paid their earnings privately and the session concluded.

The five markets were independent in the following sense. We reset the traders' initial portfolio endowments prior to each market. We also used a new independent realization of the dividends.[5] An extensive literature examining experimental markets for a finite but multi-period asset with symmetric information on the dividend process, initiated by the seminal work of Smith et al. (1988) and recently surveyed by Palan (2013), has established that mispricing is greatly dissipated after a cohort of traders has twice experienced the same market but with different dividend. We are not aware of any study which uses an asset living for as few as five trading periods. For this reason we extended the number of market repetitions.

We next provide details on our computerized implementation of the continuous double

[4]We provide a translated set of these instruction in the Appendix. Original versions in Mandarin are available upon request.

[5]Prior to the experimental session, the monitor used a bingo cage to determine the dividend sequence for each of the five markets. The monitor inserted a written record of dividend sequences into five envelopes. The monitor taped these envelopes to a platform that all traders could see during the experiment. After each market, the monitor opened the just concluded market's envelope and projected its contents. This was done to publicly confirm the dividend sequence and verify procedural integrity.

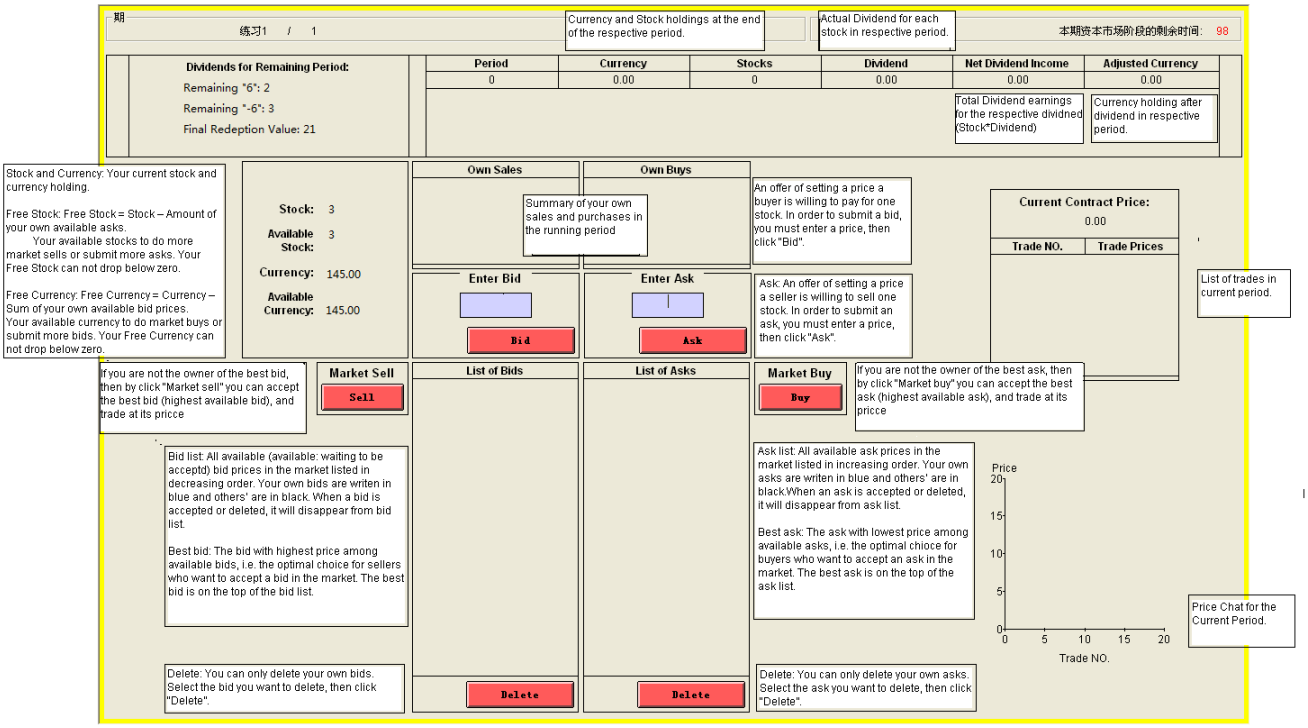

Figure 2: The trading screen of the continuous double auction

auction.[6] Each of the five trading periods in a market lasts for two minutes. Figure 2 gives a screen capture of the trading screen used in the experiment. In the top portion of the screen a trader can find information about the realized and yet unrealized dividends and her closing portfolios in each of the previous trading periods of the current market. In the middle portion of the screen she can find her current portfolio, and the amount of available pesos and asset units which she can use to make limit and market orders. We provide, in the middle of the screen, the fields by which she can make limit orders and the buttons she can use to make market orders. Below this, she can find the order book. In the lower right portion, she can find a list and a plot of all the current period transaction prices.

We conducted all sessions at the Finance and Economics Experimental Laboratory (FEEL) at Xiamen University. All three hundred traders consisted of undergraduate or

[6]We programmed the continuous double auction experiment using z-Tree 3.2.8 (Fischbacher, 2007) by modifying code generously provided by Michael Kirchler.

Table 1: The two treatment designs

(a) Treatment design 1: 2x2 factorial treatment design on short sales and leverage constraints

		Leveraged purchase	
		No	Yes
Short sales	No	Baseline	Liquidity
	Yes	Short sale	Liquidity + Short sale

Note: for treatment design 1, we have 8 traders in each experimental session, and each trader has a portfolio endowment $(100, 3)$. Each treatment cell is applied to five experimental sessions.

(b) Treatment design 2: Three Capitalization variations

	Baseline	Competition	Big Endowment
Number of traders	8	20	8
Portfolio endowment	$(100, 3)$	$(100, 3)$	$(250, 7)/(250, 8)$

Note: each treatment cell is applied to five experimental sessions.

master students attending Xiamen University. They came from various schools, such as law, computer science, chemistry and biology. But the most represented schools, with around 40% of the traders, were economics - which houses finance majors - and management. Most participants had previous experience in other studies at FEEL, but none had any previous experience in asset market experiments. We only allowed traders to participate in a single session. We recruited subjects using the ORSEE subject recruitment system (Greiner, 2004). There were approximately 1600 students in the subject pool database from which we randomly selected members to send e-mail invitations. The e-mail invitations conveyed that the experiment would last no longer the two and one-half hours and they would receive a show-up fee of ¥10. We added a trader's earnings from the selected market to her show-up fee. These market earnings were converted from pesos to Chinese Yuan at an exchange rate of ₱3 to ¥1. There was limited liability, and if a trader had a negative pesos balance she only received her show-up fee. This affected only one out of the three hundred traders. We summarize the key points and parameters of our experiment in Table 1.

3 Results

3.1 Arbitrage

We begin with a presentation of the times series of nominal arbitrages in each experimental market. Figures 3-8 display for each treatment a stack of five plots. Each layer of a stack corresponds to one of the five experimental sessions. The vertical-axis measures the peso amount of an arbitrage: the horizontal-axis measures continuous time.[7] For each trading period we provide two pairs of numbers. The top pair reports the number of realized and unrealized sell arbitrages while the bottom pair reports the number of realized and unrealized buy arbitrages.

The midpoint of the vertical-axis is zero, and the magnitude of plotted values above this reference line are the nominal peso amounts of sell arbitrages, and the magnitude of those below are the nominal peso amounts of buy arbitrages. Let's first consider sell arbitrages. When there is an explicit sell arbitrage we mark that transaction with an upward pointing triangle: this marks when a trader accepted a limit bid that exceeded the fundamental value. When there is an implicit sell arbitrage we mark that transaction with an downward pointing triangle: this marks when a trader accepted a limit ask that exceeded the fundamental value.

We use a similar practice to mark realized buy arbitrages. We mark an explicit buy arbitrage with a downward pointing triangle, and an implicit buy arbitrage with an upward pointing triangle. We note unrealized arbitrage opportunities by black triangles plotted at the closing time of a trading period.

We feel these time series plots of all arbitrages visually convey our study's key findings. In the Baseline treatment, Figure 3 exhibits consistent arbitrages across markets with more Sell than Buy arbitrage.[8] When we allow generous leverage purchasing, see Figure 4, arbitrage

[7] We break the layer into five segments, one for each of the five market iterations. These are demarcated by the thick vertical lines. Each of these market segments is further divided into five sub-segments, one for each trading period, and is demarcated by the thin vertical lines.

[8] This is consistent with the large body of literature on experimental asset markets, but our findings extending these outcomes to a non-monotonic and certain fundamental value path.

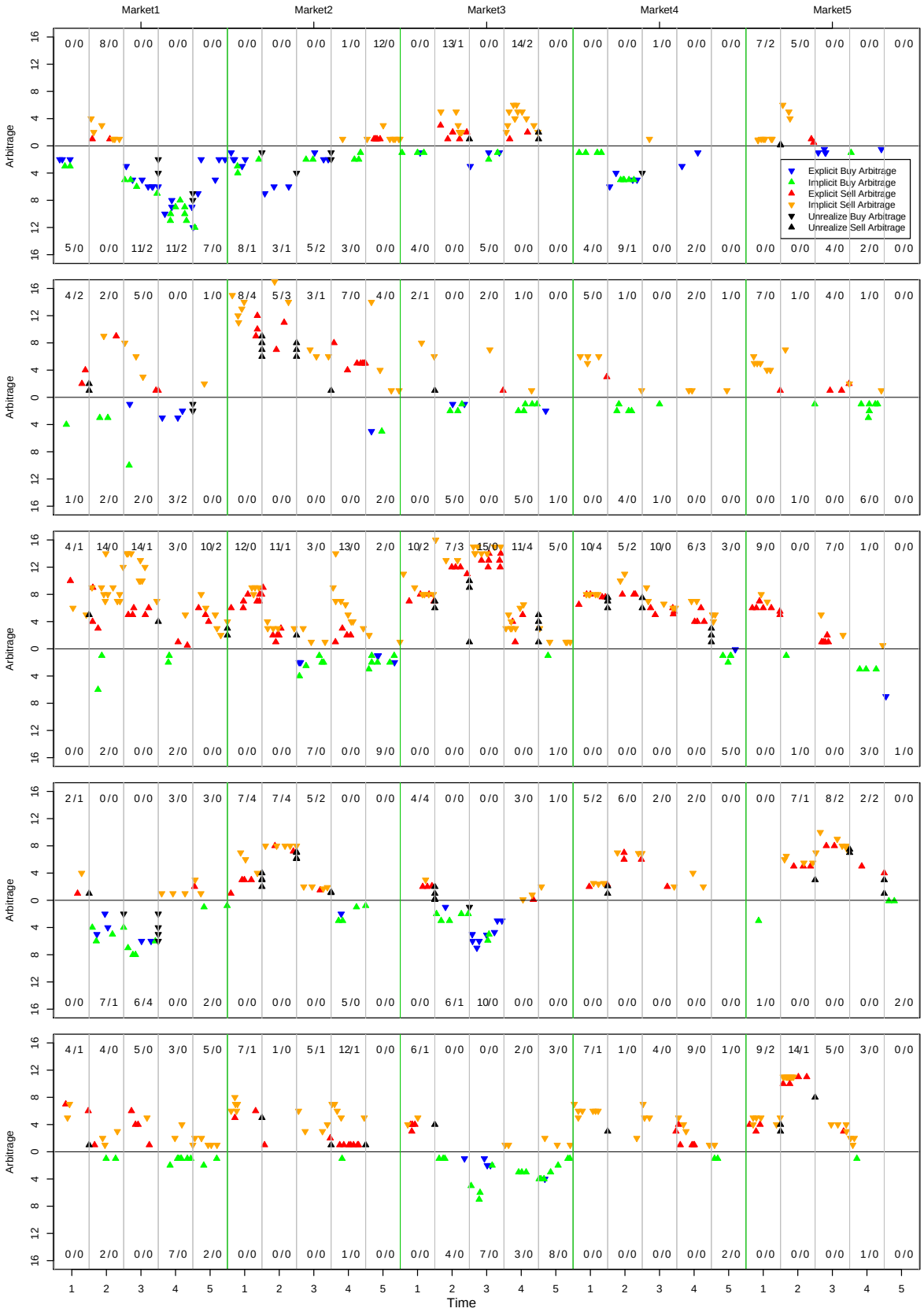

Figure 3: Arbitrage time series plots for all sessions: Baseline treatment.

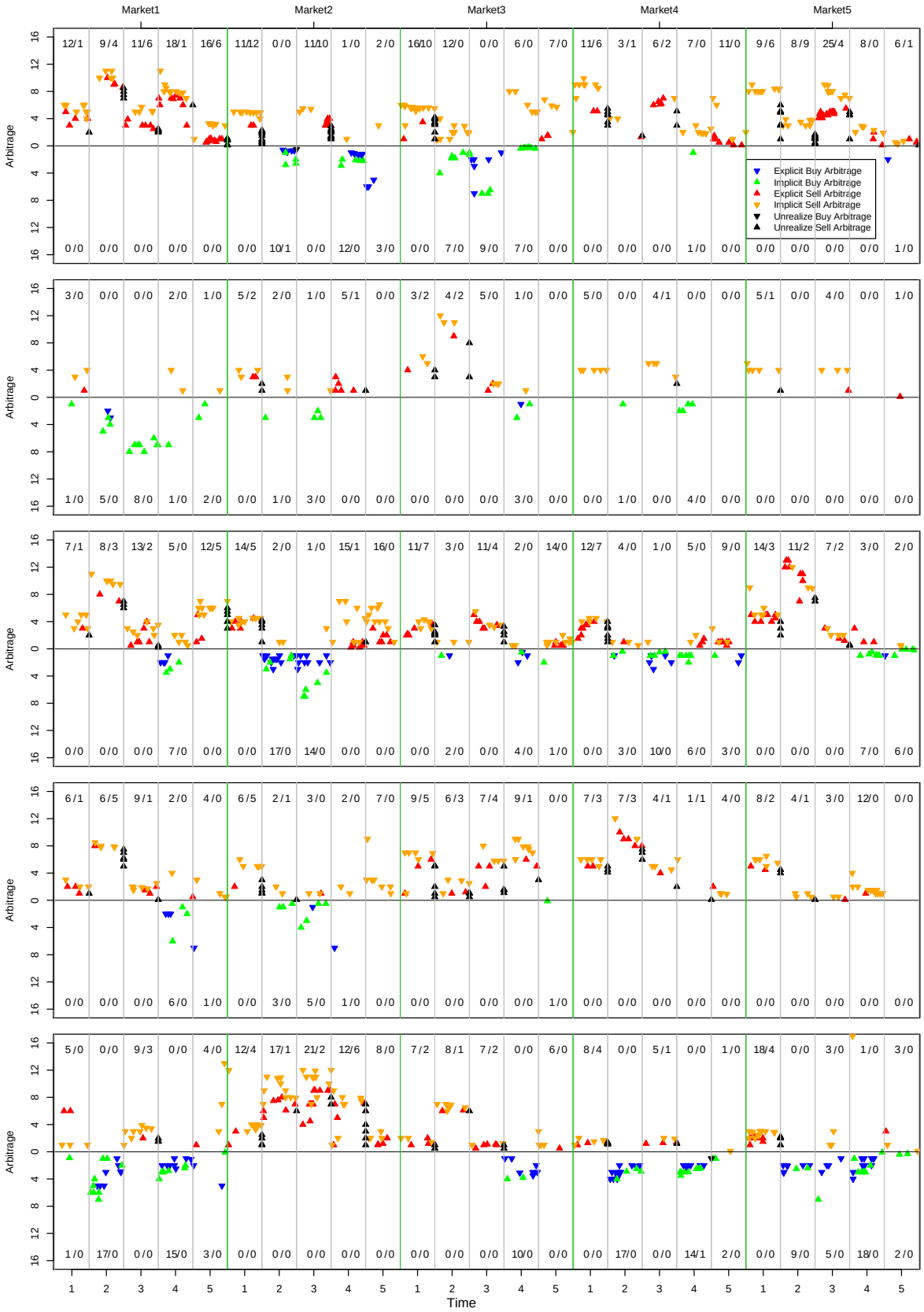

Figure 4: Arbitrage time series plots for all sessions: Liquidity treatment.

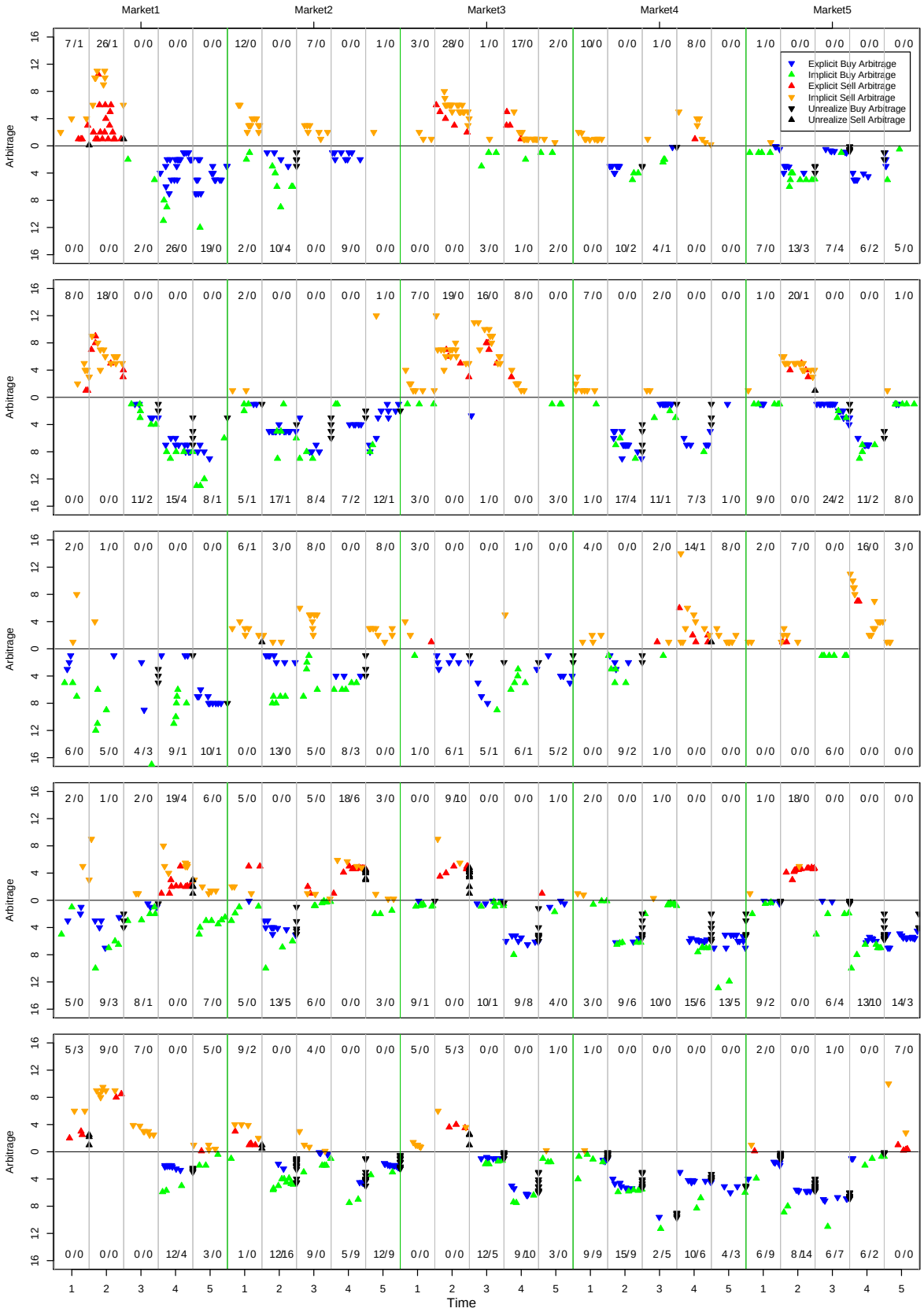

Figure 5: Arbitrage time series plots for all sessions: Short sale treatment.

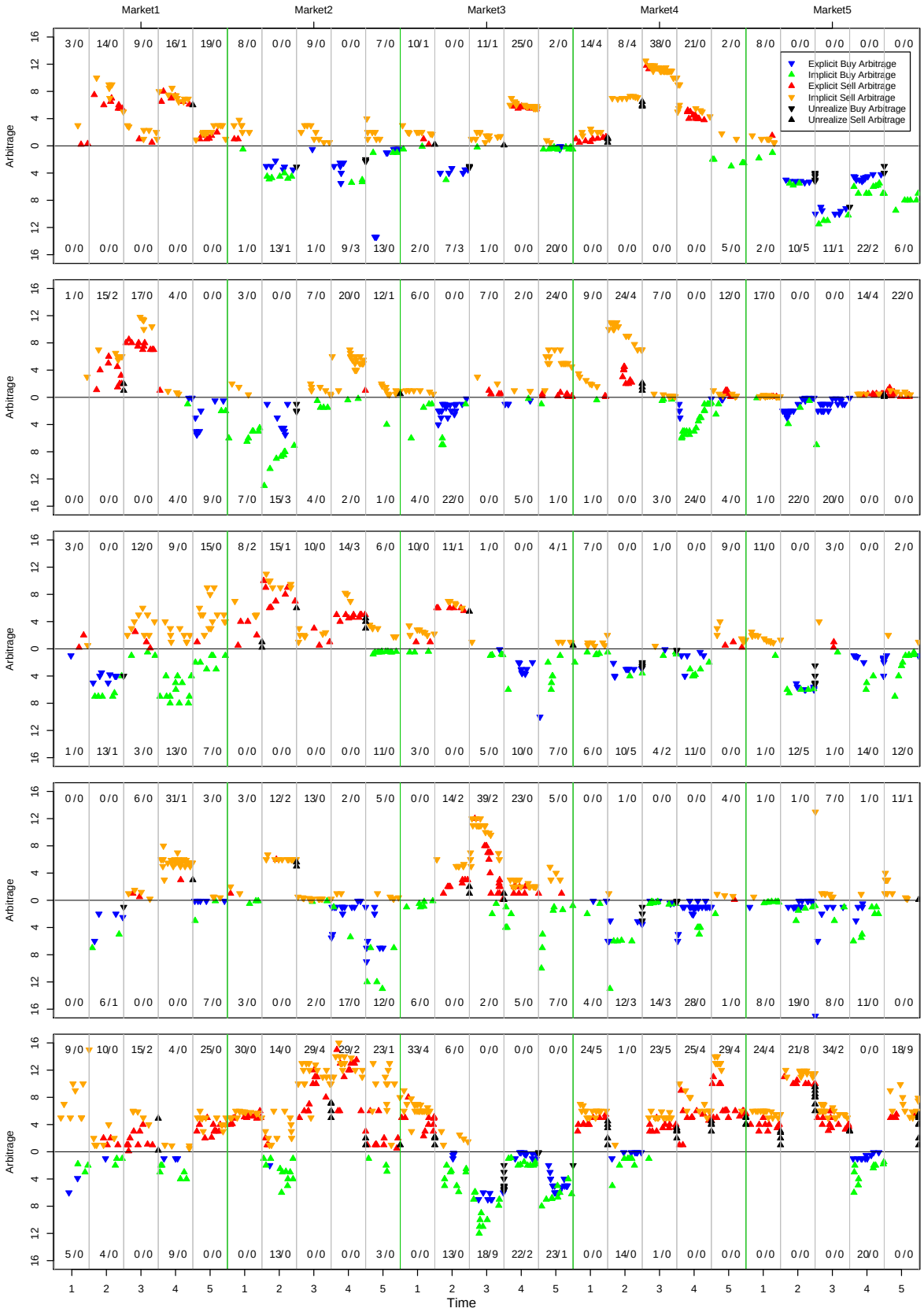

Figure 6: Arbitrage time series plots for all sessions: Liquidity + Short sale treatment.

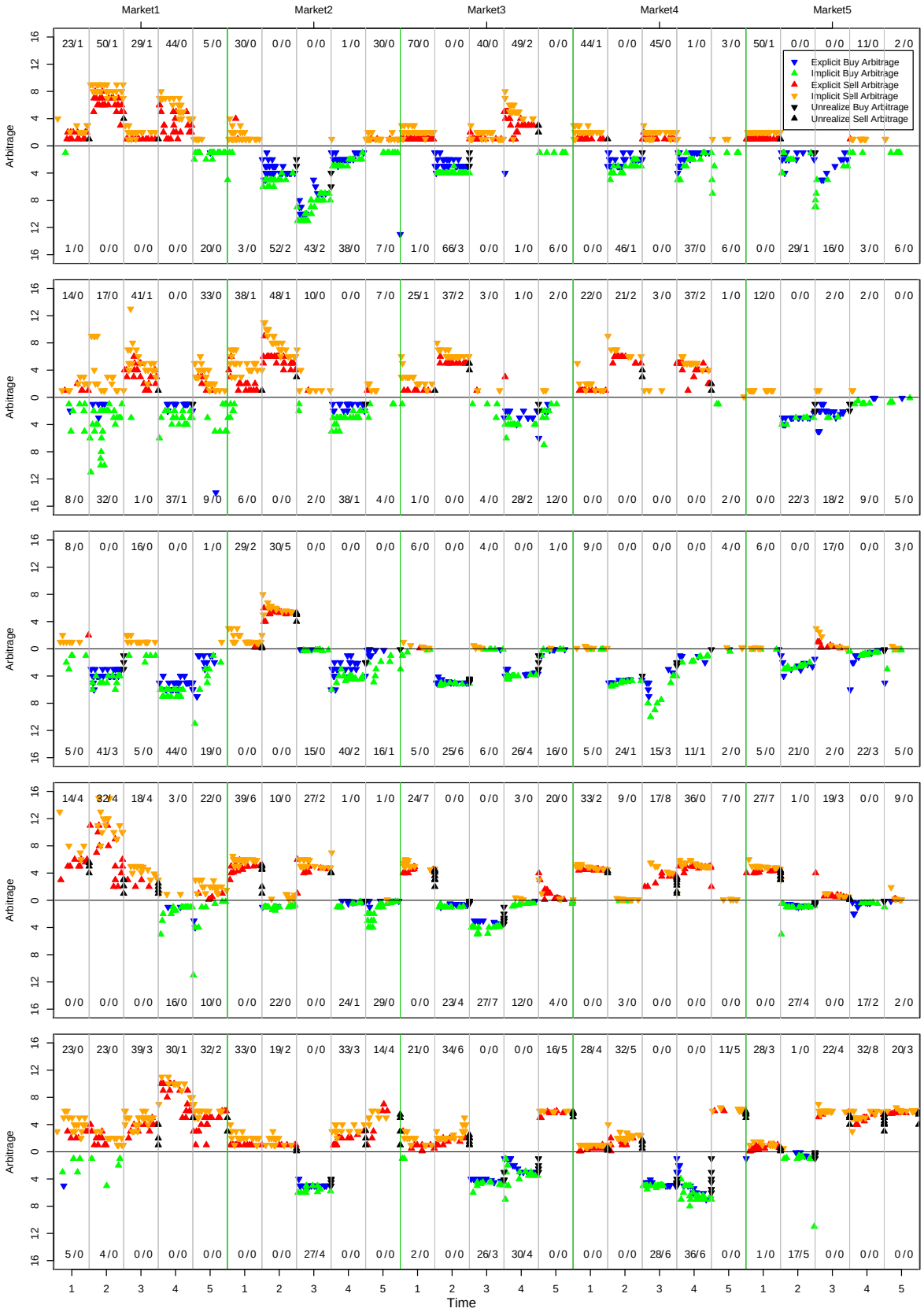

Figure 7: Arbitrage time series plots for all sessions: Competition treatment.

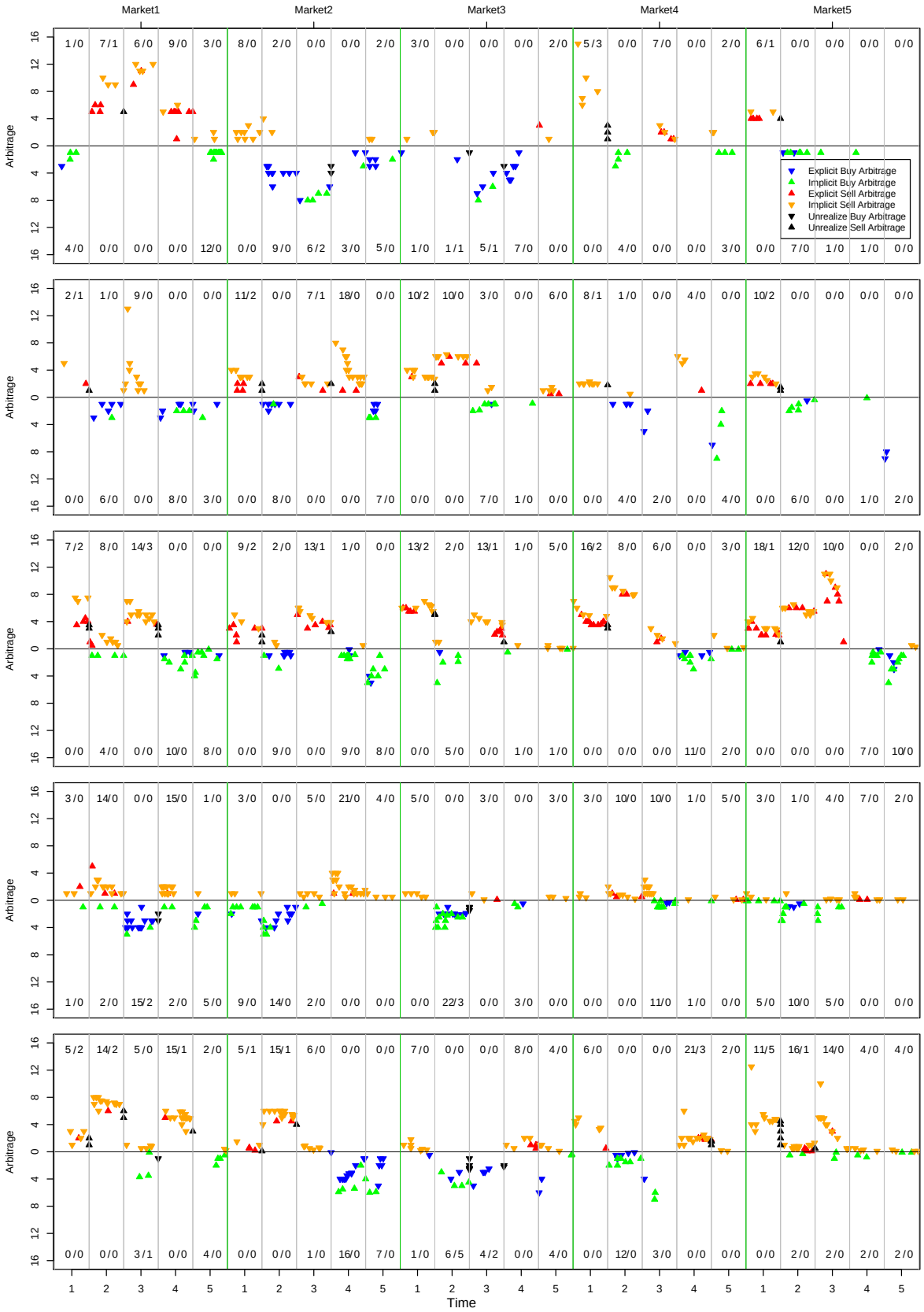

Figure 8: Arbitrage time series plots for all sessions: Big Endowment treatment.

does not diminish and becomes even more Sell arbitrage dominated. Adding Short sales, see Figure 5, does not diminish the frequency of arbitrage but does suppress prices in general; Buy arbitrage is now more frequent than Sell arbitrage. When we add both leveraged purchases and short sales, see Figure 6, we observe arbitrage of similar magnitude to the Baseline levels but with greater frequency. Returning to a world with market frictions but a larger number of traders, see Figure 7, seemingly reduces the magnitude of arbitrages but increases volume tremendously. Holding the number of participants constant but increasing the size of their portfolio endowments, see Figure 8, reduces the average size of arbitrage and its frequency.

We quantify the visually suggested effects of market frictions and capitalization by reporting summary statistics for All, Sell and Buy arbitrage by treatment in Table 2. Within each of these arbitrage types we consider implicit, explicit and either kind of arbitrage. For each category we report two statistics. The first statistic is the mean of the arbitrage magnitude conditional upon a transaction being the considered arbitrage type. The second statistic is the proportion of all trades which are of the considered arbitrage type.

Table 2: Summary statistics by arbitrage type and treatment: mean arbitrage magnitude and the percentage of trades that are of a given arbitrage category

	All Arbitrage			Sell Arbitrage			Buy Arbitrage		
	Either	Explicit	Implicit	Either	Explicit	Implicit	Either	Explicit	Implicit
Competition	3.20	2.93	3.39	3.36	3.05	3.55	2.99	2.80	3.14
	86%	36%	51%	50%	19%	30%	36%	16%	20%
Big Endowment	2.75	2.71	2.76	3.13	3.10	3.14	2.13	2.36	1.97
	81%	25%	56%	50%	12%	38%	32%	13%	18%
Baseline	4.70	4.55	4.79	5.41	5.00	5.65	3.16	3.53	2.95
	88%	33%	55%	60%	23%	38%	28%	10%	18%
Liquidity	3.69	3.05	4.10	4.20	3.50	4.58	2.36	2.17	2.53
	91%	35%	56%	66%	23%	43%	25%	12%	13%
Short sale	3.86	3.74	3.98	3.77	3.65	3.81	3.93	3.77	4.15
	89%	42%	47%	35%	10%	25%	54%	31%	22%
Liquidity + Short sale	4.19	3.55	4.62	4.93	4.45	5.19	2.98	2.49	3.44
	89%	35%	54%	55%	19%	36%	34%	16%	18%

The Baseline treatment generates the largest magnitude of arbitrage with an average of ₱4.70. Increasing capitalization by Competition or Big Endowment reduces the magnitude

of the arbitrage to ₱3.20 and ₱2.75 respectively. These reductions are larger than we observe with leveraged purchases, ₱3.69, or short sales, ₱3.86. More over, simultaneously relaxing both types of frictions increases the average arbitrage amount to ₱4.19: counter to what we expect to happen when liberating the invisible hand.

Also, Sell arbitrage is more prevalent than Buy arbitrage in terms of magnitude and proportions. In fact, the majority of trades are Sell arbitrages in all treatments. The Short sale treatment is the exception. The magnitude of Sell arbitrage in this treatment is the lowest of the non-capitalization treatments. Further, Sell arbitrage only makes up 35% of the total transactions, while Buy arbitrage makes up the majority, 54%. This is consistent with Haruvy and Noussair (2006) who find that short sales tend to dampen prices, but not establish rational expectation ones.

Table 2 also provides insights into the microstructure of how arbitrage occurs. In all treatments, Implicit arbitrage occurs more frequently than Explicit arbitrage. Further in all cases, except for Buy arbitrage in the Baseline and Big endowment treatments, the average magnitude of Implicit exceeds Explicit. In sum the most frequent and largest arbitrage is more likely to be achieved by submitting a limit ask above the fundamental value.

We provide further statistical evidence of our results and investigate the dynamic evolution of arbitrage in our markets through linear regression analysis. The average arbitrage amount in a trading period is our unit of observation, and we filter out periods where there are no arbitrages. The varying number of arbitrages across periods introduces a structural form of heteroskedasticity. Accordingly, we use a Weighted Least Squares regression model.[9] For concern out of other forms of heteroskedasticity we use robust standard errors clustered at the session level when we make statistical inferences.

We report the results of these WLS regressions in Table 3 for three dependent variables: All, Sell and Buy arbitrage. For each of these dependent variables we first estimate a simple

[9]If we assume that the unobserved error of each arbitrage is independently and identically distributed, then the variance of the period average is inversely proportional to the number of arbitrages. To correct for this we use the efficient weighted least square regression technique, (Houthakker, 1951), by which multiply the values of the dependent and independent variables by the square root of the respective period's arbitrages.

treatment dummy-variable model. Notice this simply recreates the values given in Table 2. In these dummy-variable models, the t-statistics confirm that the capitalization treatments reduce the magnitude of All and Sell arbitrage, but only the Big endowment treatment significantly reduces this magnitude for Buy arbitrage. Removing market frictions does not reduce the magnitude of any type of arbitrage. In the second version of the WLS models we control for dynamic effects by introducing the variables Market iteration, to capture learning across asset lives, and Trading period, to control for the constriction of dividend paths with the number of periods.[10] Here we find there is a statistically significant, but low-valued, learning trend across Market iterations; but the treatment effects are robust to adding this control. Our final models include the period's fundamental value. We find this is significant, negative for Sell arbitrage and positive for Buy arbitrage. The magnitudes of the estimated coefficients in these cases is less than 0.3, suggesting Sell arbitrage shrinks at high valuations while Buy arbitrage shrinks at low valuations.

[10]Note, we have zero indexed these two variables, so that constant term reflects the average magnitude of arbitrage of trading period 1 in the first Market iteration.

Table 3: Weighted least square regression results for All, Sell, and Buy Arbitrage. t-statistics reported in parentheses. We use robust standard errors clustered at the session level in our statistical analyses.

	All Arbitrage			Sell Arbitrage			Buy Arbitrage		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
Competition	-1.50*	-1.50*	-1.44*	-2.05*	-2.11*	-2.16	-0.17	-0.075	-0.039
	(-2.22)	(-2.21)	(-2.31)	(-2.33)	(-2.40)	(-2.07)	(-0.25)	(-0.11)	(-0.04)
Big endowment	-1.96**	-1.94**	-1.95*	-2.27**	-2.28**	-2.30*	-1.03*	-0.96*	-0.64
	(-2.89)	(-2.88)	(-2.62)	(-2.81)	(-2.87)	(-2.29)	(-2.32)	(-2.27)	(-1.06)
Constant	4.70***	5.40***	6.94***	5.41***	6.07***	9.88***	3.16***	3.51***	-0.78***
(Baseline level)	(7.16)	(6.54)	(7.62)	(6.26)	(6.17)	(7.39)	(6.13)	(5.75)	(-6.04)
Liquidity	-1.01	-0.97	-0.77	-1.21	-1.19	-0.61	-0.80	-0.71	-1.28
	(-1.10)	(-1.07)	(-0.91)	(-1.06)	(-1.07)	(-0.51)	(-1.25)	(-1.11)	(-1.40)
Short sale	-0.84	-0.78	-0.78	-1.64	-1.67	-2.41*	0.77	0.90	1.22
	(-1.44)	(-1.39)	(-1.45)	(-1.83)	(-2.07)	(-2.58)	(1.10)	(1.31)	(1.42)
Liquidity	-0.51	-0.38	-0.47	-0.48	-0.41	-0.73	-0.18	0.044	0.22
+ Short sale	(-0.46)	(-0.36)	(-0.45)	(-0.34)	(-0.30)	(-0.48)	(-0.38)	(0.10)	(0.45)
Market iteration		-0.25**	-0.19*		-0.22*	-0.10		-0.25*	-0.30**
		(-3.65)	(-2.28)		(-2.64)	(-1.05)		(-2.60)	(-3.78)
Trading period		-0.15	-0.048		-0.15	-0.087		0.011	-0.15
		(-1.34)	(-0.45)		(-0.80)	(-0.58)		(0.10)	(-1.51)
FV			-0.11***			-0.29***			0.23***
			(-4.69)			(-7.47)			(5.51)
R^2	0.05	0.07	0.13	0.07	0.09	0.30	0.06	0.09	0.29
Observations	731	731	731	543	543	543	430	430	430

3.2 Market efficiency

Efficient market theories often rely upon a no-arbitrage assumption. This relationship is abundantly clear in our set-up. Our dividend process renders every mis-priced transaction an arbitrage. In this subsection we investigate how our various treatments impact market efficiency. Here we focus on price deviations from the fundamental value, as symmetric information and homogeneous traders' preferences make price efficiency a sufficient condition for market efficiency. Here we find that differential degrees of arbitrage leads to similar differences in market efficiency.

The summary statistics in Table 4 suggest that increases in capitalization improve market efficiency, while the relaxations of market frictions fail to do so. The first column, FV, reports the average realized fundamental value across trading periods and the second column, Price, reports the average of the average price within periods. We report the results of t-tests that Price = FV, by using dagger indicators for rejections. We reject no price bias for the Baseline and all of the market friction treatments, but we fail to reject no price bias in the capitalization treatments. In the last column we report the average volume of transactions in a period. Remarkably, volume is statistically greater in all treatments relative to the Baseline. Both the Competition and Liquidity + Short Sale treatments have very high volumes.

The next four columns of Table 4 report various commonly used price efficiency measures(Stöckl et al., 2010) and compare them to the Baseline levels. The third column, PD, is the average difference of the average transaction price of a period and the fundamental value; the second column value less the first column value. In this case we evaluate whether this deviation is statistically differs from the Baseline treatment. Here we find our two capitalization treatments have smaller price biases. The Short sale treatment has a lower bias, but is in fact negative and of a similar magnitude as the Baseline.

Under PD a positive and negative price deviation will tend to cancel each other out. To counter this, we examine the average absolute price deviation, APD. Under this measure we

Table 4: Summary statistics for Market Efficiency

	FV	Price	PD	APD	RPD	RAPD	Volume
Big endowment	17.50	18.15	0.66***	2.22***	0.12	0.19	9.87***
	(6.29)	(4.92)	(3.17)	(2.35)	(0.46)	(0.43)	(5.00)
Competition	17.21	17.81	0.61***	2.56**	0.11*	0.20*	30.41**
	(5.20)	(3.77)	(3.38)	(2.28)	(0.36)	(0.32)	(11.87)
Baseline	17.21	19.08†††	1.95	3.39	0.22	0.29	6.48
	(5.73)	(4.59)	(4.27)	(3.24)	(0.56)	(0.53)	(3.55)
Liquidity	18.74	20.86†††	2.17	3.01	0.20	0.24	9.23***
	(5.94)	(4.16)	(3.36)	(2.63)	(0.38)	(0.36)	(5.18)
Short sale	16.92	15.70††	-1.22***	3.11	0.00***	0.20	10.85***
	(5.20)	(2.57)	(3.88)	(2.62)	(0.33)	(0.26)	(5.05)
Liquidity + Short sale	16.44	17.50††	1.06*	3.10	0.19	0.28	17.40***
	(5.56)	(3.77)	(4.08)	(2.85)	(0.54)	(0.49)	(7.98)

Note 1: PD refers to Prices Deviation. $PD = Price - FV$, where FV refers to the fundamental value of the asset. APD refers to Absolute Price Deviation. $APD = |Price - FV|$. RPD refers to Relative Price Deviation. RPD $= (Price - FV)/FV$. RAPD refers to Relative Absolute Deviation= $|Price - FV|/FV$.
Note 2: In the table, we reported the mean values of these measurements. The standard deviations are in parentheses.
Note 3: We conducted t tests to examine the difference between the baseline and other treatments. If we observe the measurement in a treatment is significantly below that in the baseline, then we use *s indicate p-value of t test. $***p < 0.01, **p < 0.05, *p < 0.1$. If we observe the measurement in a treatment is significantly above that in the baseline, then we use +s indicate p-value of t test. $\dagger\dagger\dagger p < 0.01, \dagger\dagger p < 0.05, \dagger p < 0.1$.

find only the capitalization treatments lead to a significant increase in market efficiency.

Some may argue that proportional price deviations are more meaningful than nominal deviations. In our environment the fundamental value can range from ₱3 to ₱33, which could lead to meaningful proportional differences. Columns 5 and 6 of Table 4 report the average relative price deviations, RPD, and the relative absolute price deviations, RAPD. We only marginal evidence of market efficiency for the Competition treatment in terms of these two measures.

3.3 Terminal portfolios and wealth distributions

Arbitrage, in our setting, generates wealth redistribution. A clear welfare concern is how do market frictions and capitalization impact wealth inequality. Figure 9 depicts wealth inequality and heterogeneity of terminal portfolios through an array of density plots. In the Baseline plot, there is a noticeable clustering of corner portfolios, either all pesos or all asset, suggesting market frictions are binding. When we allow just short sales there is a

predictable spread of terminal portfolios holding negative asset quantities. Moreover, traders appears to have heterogeneous capabilities in managing this market feature. A number of traders' portfolios lie near the zero wealth line, including some who have lost all of their peso and asset endowments. Introducing just liquidity results in a spread of leveraged terminal portfolios, but not as many near zero wealth portfolios as in the Short sale treatment. In the Liquidity + Short sale treatment the diversity of terminal portfolios and wealth distributions is more extreme than one would get from simply summing the "spreads" of the Liquidity and Short sale treatments.

Our two forms of increased capitalization both effectively reduced arbitrage and market inefficiencies, but appear to have differential impact on terminal portfolios and wealth distributions. In the Big endowment treatment, we divide the terminal values by two and one-half to put it on the same scale as the other treatments. Here we see density massed on interior portfolios and little dispersion in wealth. The Competition treatment has more profound impact. We see mass is more concentrated on the corner portfolios. Further there is an increasing variance in wealth as the final asset holdings go to zero. There are also a number of traders who seem to "lose it all."

We quantify the relative inequality of wealth distributions by calculating the Gini coefficient[11] of the terminal wealth levels given in Figure 9. We report these values in Table 5. These Gini coefficients confirm our observations that one finds the lowest wealth inequality in our Big endowment treatment, and the greatest inequality in the Competition and Liquidity + Short sale treatments. We find this result regarding the Competition treatment surprising. On one hand, the tremendous increase in liquidity, both in terms of total values of limit orders and the number of orders in the books, reduces arbitrage - and in turn inducing greater market efficiency. But on the other hand, this form of increased competition drives greater wealth inequality.

[11]The Gini coefficient is defined a $G = \sum_{i=1}^{M}\sum_{j=1}^{M}\sum_{s=1}^{5}\sum_{t=1}^{5}|w_{i,s} - w_{j,t}|/2M\sum_{i=1}^{M}\sum_{s=1}^{5} w_{i,s}$, where M is the total number of traders in a treatment, 40 in all except for 100 in the Competition treatment, and $w_{i,s}$ is trader i's earnings in Market s.

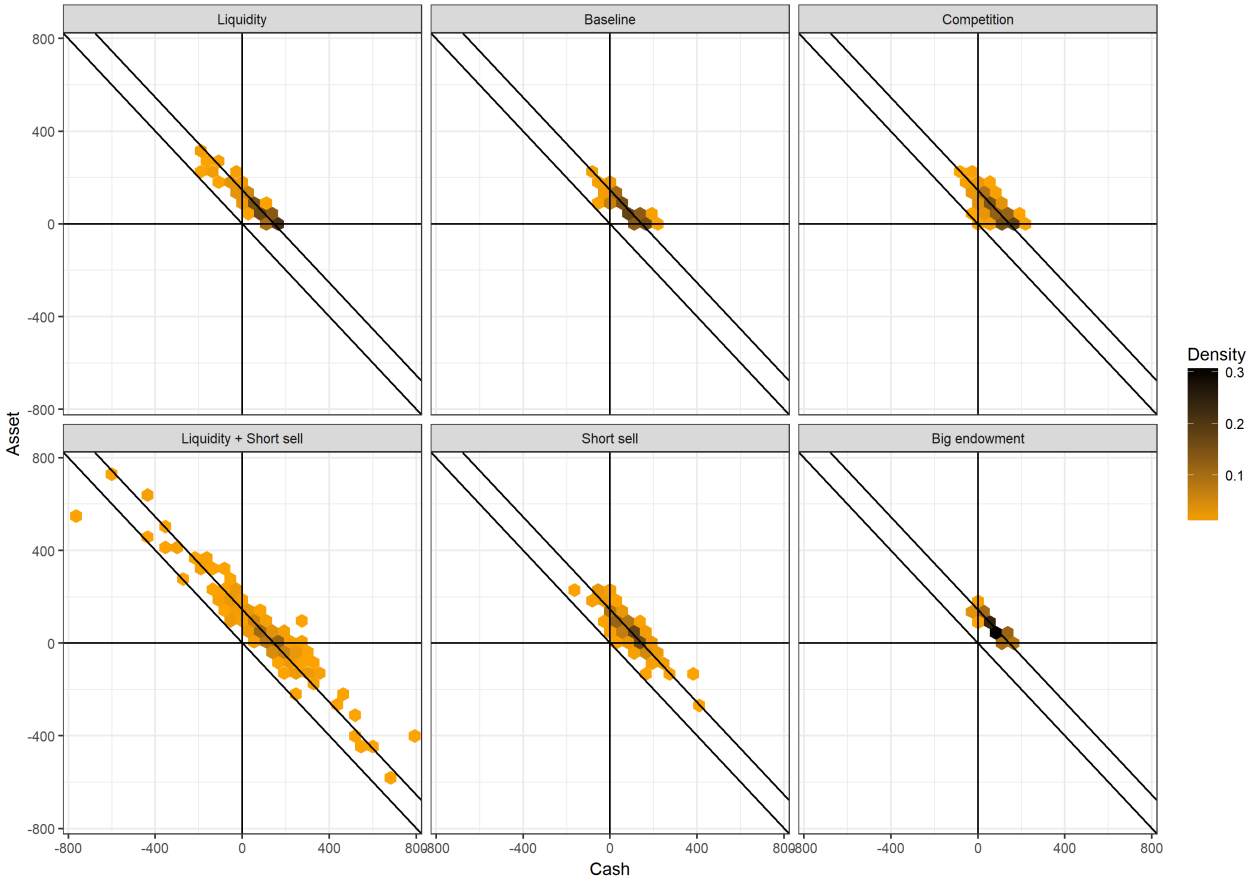

Figure 9: The empirical distributions of terminal portfolios plotted by hexagonal binning. Each asset unit held is by its terminal ₱21 redemption. The two reference lines with slope of -1 represent equi-wealth portfolios of the initial endowment and zero.

Table 5: Gini Coefficient of terminal wealth for each treatment

Treatment	Gini Coefficient
Competition	0.098
Big endowment	0.032
Baseline	0.078
Liquidity	0.071
Short sale	0.118
Liquidity + Short sale	0.192

References

De Bondt, W. F. M. and Thaler, R. H. (1985). Does the stock market overreact? *Journal of Finance*, 40(3):793–805.

De Long, J. B., Shleifer, A., Summers, L. H., and Waldmann, R. (1990). Noise trader risk in financial markets.

Fischbacher, U. (2007). z-tree: Zurich toolbox for ready-made economic experiments. *Experimental economics*, 10(2):171–178.

Greiner, B. (2004). An online recruitment system for economic experiments.

Haruvy, E. and Noussair, C. N. (2006). The effect of short selling on bubbles and crashes in experimental spot asset markets. *The Journal of Finance*, 61(3):1119–1157.

Houthakker, H. S. (1951). Some calculations on electricity consumption in great britain. *Journal of the Royal Statistical Society. Series A (General)*, 114(3):359–371.

Palan, S. (2013). A review of bubbles and crashes in experimental asset markets. *Journal of Economic Surveys*, 27(3):570–588.

Radner, R. (1979). Rational expectations equilibrium: Generic existence and the information revealed by prices.

Shleifer, A. and Vishny, R. W. (1995). The limits of arbitrage. (5167).

Smith, V. L., Suchanek, G. L., and Williams, A. W. (1988). Bubbles, crashes, and endogenous expectations in experimental spot asset markets. *Econometrica*, 56(5):1119–51.

Stöckl, T., Huber, J., and Kirchler, M. (2010). Bubble measures in experimental asset markets. *Experimental Economics*, 13(3):284–298.