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AN EXPERIMENTAL ANALYSIS ON CROSS-ASSET ARBITRAGE OPPORTUNITY AND THE LAW OF ONE PRICE

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An experimental analysis on cross-asset arbitrage opportunity and the law of one price*

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Abstract

This study experimentally investigates the impact of the lack of arbitrage opportunities across different assets on the realization of the law of one price. Our experiment is based on the framework established by Charness and Neugebauer (2019) where participants, acting as traders, are involved in transactions with two different types of assets. An increase in the magnitude of price discrepancies and fundamental mispricing are observed when traders are unable to engage in arbitrage between different assets. The presence of opportunities for cross-asset arbitrage typically prompts traders to pay closer attention to the pricing of an alternative asset during transactions, which effectively reduces the extent of price discrepancies and mispricing.

JEL Code: C90, D84

Keywords: The law of one price, Arbitrage opportunities across different assets, Price discrepancy, Asset Pricing,

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1 Introduction

In a competitive market where traders engage in transactions with multiple distinct assets, the law of one price stipulates that the returns on these assets should be equalized through arbitrage (Childs and Mestelman, 2006).

Nonetheless, a growing volume of research suggests that the law of one price is not consistently upheld—the occurrence of price discrepancies, which signal deviations from the law of one price, as documented in both empirical and experimental studies. An empirical analysis by Owen and Thaler (2003) found price discrepancies in situations involving closed-end country funds, twin shares, dual-class shares, and even corporate spin-offs, attributing these anomalies to the restricted capacity of rational arbitrageurs to act. Experimental studies by Childs and Mestelman (2006) and Chan et al. (2013), which introduced twin market setups, revealed that magnitudes of price discrepancy are linked to differences in asset properties. While Childs and Mestelman (2006) noted increased price discrepancies with divergent expected dividend values, Chan et al. (2013) observed reduced discrepancies under similar conditions, arguing that differences in asset characteristics promote cross-asset arbitrage, thus significantly curtailing mispricing.

Further experimental scrutiny of the Modigliani-Miller invariance theorem (MM theorem), such as Levati et al. (2012) and Charness and Neugebauer (2019), have also highlighted breaches of the law of one price, with both studies attributing these deviations to the absence of arbitrage opportunities across different assets. In particular, Charness and Neugebauer (2019) observed significant price discrepancies when trading a leveraged and an unleveraged asset simultaneously, especially when the future dividend processes of these assets were uncorrelated. They posited that the presence of arbitrage risk in future uncorrelated dividend processes deterred traders from engaging in arbitrage, leading to pronounced price discrepancies.

The aforementioned interpretations, however, appear to be at odds with conventional economic theories (e.g., Hirshleifer, 1966; Stiglitz, 1969) which posit that the lack of arbitrage opportunities should not affect the level of price discrepancies or mispricing, as arbitrage within each asset is expected to correct mispricing relative to fundamentals, thereby reducing price discrepancies. Therefore, this perspective from traditional economic theories stands in opposition to the explanations provided by the aforementioned experimental studies.

To the best of our knowledge, no study has directly explored price discrepancies by deliberately manipulating arbitrage opportunities between different assets within a laboratory setting. This gap in the literature creates ambiguity regarding the connection between arbitrage opportunities across distinct assets and the achievement of the low of one price. Consequently, this research aims to examine the relationship between cross-asset arbitrage and price discrepancies through a controlled laboratory experiment.[1] Should the lack of arbitrage between different assets indeed lead to price discrepancies, as some literature suggests, then limiting arbitrage opportunities across different assets might exacerbate these discrepancies.

To ensure comparability with existing experimental literature, our experimental design is based on Charness and Neugebauer (2019), utilizing the framework estab-

[1] This study is not the inaugural investigation into the role of traders' arbitrage behavior in financial asset bubbles through experimental methods. For instance, Noussair and Tucker (2006) explored the dynamics between spot market bubbles and the futures market, discovering that bubbles were less likely to occur in spot markets when futures markets were incorporated into the experimental design. This suggests that arbitrage between spot and futures markets could mitigate price bubbles. Duffy et al. (2022) assessed the impact of exchange-traded funds (ETFs), favored by institutional investors for arbitrage opportunities, on asset pricing and market turnover in a laboratory setting. Their findings indicate that in scenarios of negatively correlated dividends, ETFs contribute to the reduction of asset mispricing without diminishing market activity. Additionally, an empirical investigation by Ben-David et al. (2018) revealed that ETF arbitrage activities heightened the non-fundamental volatility of underlying stocks, attributed to the actions of noisy traders. Despite these contributions, existing research has not definitively addressed whether the lack of arbitrage opportunities across different assets exacerbates price discrepancies.

lished by Smith et al. (1988)[2]. Participants, in the role of traders, engage in transactions with two distinct types of financial assets. Despite having identical risk profiles, these assets differ in their fundamentals. The future dividend processes of these assets are perfectly positively correlated, and transactions are conducted using experimental currency. The experiment features two treatments: in one, traders can transact both asset types simultaneously, allowing for cross-asset arbitrage; in the other, traders are limited to transactions with just one asset type, precluding cross-asset arbitrage. In both treatments, traders have access to the latest transaction and average prices of all asset types, enabling them to gather trading information about the other asset type regardless of their treatment.

Our findings indicate that the absence of arbitrage opportunities significantly increases both the magnitude of price discrepancies and the degree of mispricing from fundamentals, aligning with the suggestions of Charness and Neugebauer (2019), Chan et al. (2013), and Levati et al. (2012).

Moreover, we find that the opportunity for cross-asset arbitrage often leads traders to concentrate on the pricing of an alternative asset during specific asset transactions, which in turn helps reduce the magnitude of price discrepancies and mispricing.

The rest of the paper is organized as follows. Section 2 describes the experimental design. Section 3 outlines the Measures and hypotheses. Section 4 provides an analysis of the data. Finally, Section 5 offers some conclusions.

[2]A substantial number of experimental studies have utilized this framework to explore the underlying causes of asset bubbles. Comprehensive surveys of these studies are provided by Palan (2013), Powell and Shestakova (2016), Nuzzo and Morone (2017), Duffy et al. (2022). and Angerer et al. (2023)

2 Experimental Design

2.1 Basic experimental design

Our experimental design extends that of Charness and Neugebauer (2019). The experiment comprises three finite horizon economies, with each economy, termed a 'sequence', consisting of $T = 10$ discrete trading periods. Within each trading period, participants can engage in buying and selling of two distinct types of multi-period-lived assets in continuous double-auction markets, using the experimental currency denominated as "Cents".

For two distinct types of multi-period-lived assets, one is denoted as "A-share." This asset pays its holders dividends drawn from {0, 8, 28, or 60 cents} with equal probability at the end of each period. In contrast, the other asset denoted as "B-share," consistently pays dividends 24 cents higher than the A-share at the end of each period. Upon the conclusion of each sequence, all held shares are forfeited without compensation. Consequently, the fundamental value of each share type, during each period, equates to the expected dividend value of the remaining period. Within this framework, the fundamental value of B-shares, at the beginning of each sequence, is 24×10 cents higher than that of A-shares, despite their equivalent risk levels. In each sequence, there are 14 traders equally distributed into two types: Type A and Type B. The primary distinction between these two trader types lies in their endowments.

Specifically, at the outset of the sequence (t=1), each Type A trader receives an endowment of 6 units of A-share and 1,200 cents of experimental currency. Conversely, each Type B trader receives an endowment of 3 units of B-share and the same 1,200 cents of experimental currency. Table 1 shows the initial individual endowments of each type of trader, expected dividend value, and initial total variance for each type of share.

Table 1: Initial Individual Endowments, Expected Dividend Values and Variances

	Trader	Initial unit endowment	Expected dividend value/unit	Initial total Variance/unit
A-shares	Type A trader	6	$24 \times (T - t + 1)$	$536 \times (T - t + 1)$
	Type B trader	0		
B-shares	Type A trader	0	$48 \times (T - t + 1)$	$536 \times (T - t + 1)$
	Type B trader	3		
Cents	All trader	1200	1	-

Note: The third column delineates the individual unit endowments in shares and cents for each type of trader. The fourth and fifth columns enumerate the expected values and variances of each share type's dividend, respectively. Given that $t \leq T = 10$, the expected payoffs for the A-share and B-share are 240 and 480 cents, respectively, with an initial total variance for each share being 5360. Over time, both the variances and expected dividend values exhibit a linear decline.

Moreover, all traders were able to borrow up to 2,400 cents for the purchase of assets and could short-sell up to four units of A-share and up to four units of B-share without any margin requirements. The trading flow was unaffected (i.e., there was no message indicating a short sale rather than a long sale) by short sales and borrowings, which were displayed as negative numbers. The shorted share pays a negative dividend to the holders.

To reduce confusion and in turn pricing discrepancies, participants were reminded on screen about the sum of expected dividends for the remaining periods. Dividends, prices (open, low, high, closing, and average), number of transactions, and portfolio compositions in each past period were reported in tables.

2.2 Trading mechanism

The experiment adopts an open-book continuous double-auction mechanism. Each trading period lasts 180 seconds in the first sequence and lasts 90 seconds in the remaining sequence. There are two markets, one for trading A-shares and the other one for trading B-shares. Once trading begins, traders can submit a bid (a buy order) and/or an ask (a sell order) for a unit of shares in continuous time in these markets simultaneously. Traders are allowed to transact as many units of shares as they desire until the countdown timer expires for each period. within their budget constraint. A transaction takes place when the best bid and the best ask cross, at the price determined by whichever is submitted earlier. Once a transaction takes place, cash and shares holdings are immediately updated, and all the outstanding bids of the buyer and all the outstanding offers of the seller are canceled in both markets.

2.3 Treatments

The experiment incorporates two treatments, wherein the presence of arbitrage opportunities between A-shares and B-shares is varied. Specifically, the treatment denoted below as W treatment permits traders to engage in arbitrage across A-shares and B-shares, adhering to the basic experimental design outlined above. Within this treatment, all traders have the ability to transact both types of shares simultaneously. Conversely, in the treatment denoted as WO treatment, traders are restricted to trading shares corresponding to their types. Hence, traders categorized as type A can only transact A-shares, while those categorized as type B can only transact B-shares. Additionally, type A traders can short up to 12 units of A-shares but are prohibited from shorting B-shares, whereas type B traders have the capability to short up to 6 units of B-shares but are restricted from shorting A-shares. As a result, traders within this treatment are precluded from engaging in arbitrage across the two share types.

2.4 Payment

Upon the conclusion of each sequence, the cents held are converted to Japanese Yen (JPY) at an exchange rate of $1cent = 2JPY$, serving as the earnings of the participants for that sequence. After the experiment concludes, a computer randomly selects one sequence to calculate the participants' earnings. Participants receive cash payments based on their earnings in the selected sequence, in addition to a 1500 JPY participation fee. If a participant incurs negative earnings in the selected sequence, the amount will be deducted from the participation fee; however, the total payment from the experiment did not fall below 1000 JPY.

2.5 Data collection

The experiment was executed utilizing z-Tree (Fischbacher, 2007) and conducted at the experimental laboratory of the Institute of Social and Economic Research at Osaka University from October 2022 to January 2023. All participants were students enrolled at Osaka University, recruited through the ORSEE recruiting system (Greiner, 2015).

Each treatment comprised 8 groups, with each group consisting of 14 participants, culminating in a total of 224 student participants across 16 sessions.[3]

In every session, an instructional video[4] was presented to the participants, supplemented by printed handouts for reference. A quiz was administered to ascertain participants' comprehension of the experimental rules, including the computation of their payoffs. To ensure that participants understood the rules, the experiment started only after all the participants had answered all the questions correctly. Preceding the main experiment, participants' risk attitudes were assessed utilizing the Certainty Equivalent Method following the guidelines in Healy (2016).

The average payoff amounted to 3464 JPY ($\approx 30.48\ USD$, based on the prevailing

[3]However, in analyzing the price discrepancies, the data from one group in the W treatment were identified as an outlier by the Smirnov-Grubbs test. Consequently, only the data from 15 groups, comprising 210 participants, were utilized for all subsequent analyses.

[4]The online appendix provides the English translation of the instructions.

exchange rate during the experiment period). The duration of each session ranged from two to two and a half hours. No significant differences were observed in gender distribution (Percentage of females: 33% in WO and 34% in W; Fisher's Exact Test: $p = 1$) or in risk attitudes (the average scores were 46.9 in WO and 48.6 in W; Mann-Whitney U Test: $p = 0.338$) between the two treatments.

3 Measures and Hypotheses

3.1 Measures

To accurately compare the extent of violations of the law of one price across different treatments, we utilize a measure—Log-Price Discrepancy (LPD)—that is adapted from the one introduced by Charness and Neugebauer (2019).[5] For a given group g in sequence r, LPD is defined as:

$$LPD^{g,r} = \frac{1}{T}\sum_{t=1}^{T} |\log\left(\frac{P_{B,t}^{r,g}}{P_{A,t}^{r,g} + (FV_{B,t} - FV_{A,t})}\right)| \quad (1)$$

The LPD illustrates the extent of the price discrepancy, which signifies potential gains via selling high and buying low based on average prices. The LPD is zero if the prices of A-share and B-share are equal to fundamental values or if the prices deviate from the fundamental values by the same magnitude.

Despite a zero LPD, prices may diverge from the fundamental value. To contrast the price deviations from fundamental values, we utilize the relative absolute deviation from fundamentals, denoted as RAD, which has been proposed in the literature for

[5]This measure is related to PD, which is calculated as $PD^{g,r} = \frac{1}{T}\sum_{t=1}^{T}|\frac{P_{B,t}^{r,g}}{P_{A,t}^{r,g}+(FV_{B,t}-FV_{A,t})} - 1|$ and utilized by Charness and Neugebauer (2019) to examine the extent of price discrepancies. However, we have opted not to use PD as it tends to underestimate cases where A-shares are, on average, priced higher than B-shares. For example, PD may exceed 1 if B-shares are overvalued relative to A-shares, but it will not exceed 1 when A-shares are overvalued relative to B-shares.

the single-asset market by Stöckl et al., 2010. For a specified group g in sequence r, the term $RAD_k^{g,r}$ is defined as follows:

$$RAD_k^{g,r} = \frac{1}{T}\sum_{t=1}^{T}\left|\frac{P_{k,t}^{r,g} - FV_{k,t}}{\overline{FV}_k}\right| \tag{2}$$

where $P_{k,t}^{r,g}$ represents the average transaction price of a type of shares $k \in (A, B)$ in group g at period t in sequence r, $FV_{k,t}$ denote the fundamental value of type $k \in (A, B)$ shares at period t, and $\overline{FV}_k = \frac{\sum_t FV_{k,t}}{T}$ denote the average fundamental value of type k share. The RAD_k elucidates the magnitude of the deviation of the average transaction price of type k shares from the fundamental values. RAD_k equals zero if and only if the shares' average transaction price is equal to the fundamental values in all the periods.

Lastly, to accurately compare the transaction price deviation from fundamentals for the entire market, we apply the Relative Absolute Deviation from Fundamentals of the whole market, denoted as DF, defined by Charness and Neugebauer (2019). For a specified group g in sequence r, the term $DF^{g,r}$ is defined as follows:

$$DF^{g,r} = \frac{1}{2T}\sum_{k\in\{A,B\}}\sum_{t=1}^{T}\left|\frac{P_{k,t}^{r,g} - FV_{k,t}}{FV_{k,t}}\right| \tag{3}$$

Notice the difference in the denominator between DF and RAD, while the deviation of the average price from the fundamental value in period t is normalized by the fundamental value in the same period for DF, it is normalized by the average fundamental value across all the period for RAD.

3.2 Hypotheses

According to established economic theory (e.g. Hirshleifer, 1966; Stiglitz, 1969), the absence of arbitrage opportunities between two types of shares is not a necessary condition for the law of one price to be valid. We thus state the following null hypothesis.

Hypothesis 0-1 *There are no statistical differences in LPD between W treatment and WO treatment.*

Moreover, the Rational Expectations Equilibrium (REE), as posited by standard economic theory under the risk-neutral trader assumption, suggests that the degree of mispricing for each share type remains unaffected by the existence of the arbitrage opportunities between the A-shares and B-shares. This leads us to another null hypothesis.

Hypothesis 0-2 *There are no statistical differences in* RAD_A*,* RAD_B *and DF between treatments W and WO.*

Contrarily, Charness and Neugebauer (2019) posits that the absence of cross-asset arbitrage can amplify deviations from parity pricing. If their assertion holds true, deviations from parity pricing will be more pronounced when cross-asset arbitrage opportunities are limited. This leads to the subsequent alternative hypothesis:

Hypothesis 1 *The LPD will be higher in the WO treatment than in the W treatment.*

Moreover, the result of Charness and Neugebauer (2019) shows a high level of overpricing of B-share in the treatment where the arbitrage across assets is potentially restricted compared with when it is not. This implies that restricting arbitrage opportunities across assets may increase the magnitude of mispricing. This leads to the subsequent hypothesis:

Hypothesis 2 *The RAD_A, RAD_B or DF will be higher in the WO treatment than in the W treatment.*

Finally, based on evidence of mispricing decreasing as participants repeat the sequence (Smith et al., 1988; Dufwenberg et al., 2005), we anticipate a reduction in mispricing in later sequences as traders gain experience. Thus we hypothesize:

Hypothesis 3 *The values of LPD, RAD_A, RAD_B and DF will converge towards 0 over sequence.*

4 Results and Discussions

4.1 Price Discrepancy between twin shares

Observation 1 *The absolute difference from parity, LPD is reduced in the W treatment relative to the WO treatment. Furthermore, the value of LPD declines across sequences in both treatments.*

Support: Table 2 presents the median value of LPD and a comparative analysis between treatments in Panel A, while Panel B provides the outcomes of linear regression analyses conducted on $LPD^{r,g}$.[6] Table 2, Panel A, demonstrates that the median $LPDs$ in the W treatment are statistically significantly lower than those in the WO treatment. Specifically, in Sequence 1, the difference is significant at the 5%

[6] When analyzing the median $LPDs$, the data from one group in the W treatment were flagged as an outlier by the Smirnov-Grubbs test. As a result, only the data from 15 groups were included in all subsequent analyses.

Table 2: The Log Absolute Deviation from Parity, LPD

Panel A. the median value of LPD

	W ($n=7$)	WO ($n=8$)	The $p-values$ from one-sided Mann-Whitney test between treatments (H_0: W = WO)
Sequence 1	0.075	0.122	0.036**
Sequence 2	0.076	0.104	0.116
Sequence 3	0.036	0.086	0.060*
Overall	0.071	0.108	0.027**

Panel B. The regressions on $LPD^{g,r}$

Independent variables	(1)	(2)
Intercept	-0.011	-0.030
	(0.293)	(0.294)
Treatment	0.054**	0.090**
(variable=1: WO)	(0.024)	(0.044)
The average score	0.003	0.003
on risk attitude	(0.006)	(0.006)
Sequence	-0.027***	-0.018***
	(0.007)	(0.005)
Treatment×		-0.018
Sequence		(0.013)
Adjusted R^2	0.245	0.241
Observations	45	

Note: Panel A presents the median value of LPD for each sequence and treatment. Panel B details the linear regressions conducted on $LPD^{g,r}$. In Panel B, the independent variable, $ThescoreonriskattitudeSequence$, quantifies the average risk aversion level of each group, with a lower score indicating a higher degree of risk aversion. Robust standard errors, enclosed in parentheses, are clustered by group. In both panels, *, **, and *** indicate a significant difference from 0 at the 10, 5 and 1% significance levels.

level (0.075 in W vs. 0.122 in WO); in Sequence 3, the significance is at the 10% level (0.036 in W vs. 0.086 in WO); and overall, the difference is significant at the 5% level (0.071 in W vs. 0.108 in WO), as determined by a one-sided Mann-Whitney test.[7]

In Panel B, the linear regression analyses produce consistent results. The coefficients for the dummy variable "treatment" (= 0.054, presented in the second row of the model (1)) are significantly positive at the 5% level, even after adjusting for the average score on risk attitude of each group. These findings suggest that limiting arbitrage opportunities between twin-shares amplifies the extent of price discrepancies. This supports **Hypothesis 2** and reject **Hypothesis 0-1**

This finding is consistent with those reported by Charness and Neugebauer (2019). Their experimental evidence demonstrates that price discrepancies widen when traders are unable to execute risk-free arbitrage between twin-shares.

Furthermore, in the sixth row of Panel B, the coefficients (= −0.027) associated with the variable "Sequence," which is represented by sequence numbers, are significantly negative at the 1% significance level. This indicates a reduction in the magnitude of price discrepancies as traders accrue experience across both treatments, supporting **Hypothesis 3** This finding aligns with the results reported by Charness and Neugebauer (2019).

4.2 Bubble Magnitude

We now turn our attention to RAD and DF.

Observation 2 *The median RAD_A is elevated in the WO treatment compared to the W treatment.*

[7]However, such a difference is not observed in Sequence 2 (0.076 in W vs. 0.104 in WO, p = 0.116).

Table 3: The pricing deviation from the fundamental

Panel A. the median value of RAD_A

	W ($n = 7$)	WO ($n = 8$)	The $p - values$ from the one-sided Mann-Whitney test between treatments (H_0: W = WO)
Sequence 1	0.026	0.111	0.047**
Sequence 2	0.025	0.074	0.015**
Sequence 3	0.018	0.112	0.002***
Overall	0.023	0.103	0.015**

Panel B. the median value of RAD_B

	W ($n = 7$)	WO ($n = 8$)	The $p - values$ from the one-sided Mann-Whitney test between treatments (H_0: W = WO)
Sequence 1	0.095	0.098	0.307
Sequence 2	0.055	0.036	0.307
Sequence 3	0.041	0.021	0.500
Overall	0.062	0.054	0.483

Panel C. the median value of DF

	W ($n = 7$)	WO ($n = 8$)	The $p - values$ from the two-sided Mann-Whitney test between treatments (H_0: W = WO)
Sequence 1	0.064	0.124	0.027**
Sequence 2	0.058	0.093	0.090*
Sequence 3	0.031	0.102	0.007***
Overall	0.053	0.115	0.027**

Panel D. The regressions on $RAD_A^{g,r}$, $RAD_B^{g,r}$, and $DF^{g,r}$.

	Dependent variables		
	$RAD_A^{g,r}$	$RAD_B^{g,r}$	$DF^{g,r}$
Intercept	-0.188	-0.011	0.001
	(0.458)	(0.344)	(0.333)
Treatment	0.094*	0.009	0.059**
(variable=1: WO)	(0.053)	(0.018)	(0.025)
The average score	0.006	0.003	0.002
on risk attitude	(0.010)	(0.008)	(0.007)
Sequence	-0.023	-0.033***	-0.023**
	(0.018)	(0.008)	(0.009)
Adjusted R^2	0.151	0.157	0.178
Observations		45	

Note: Panels A, B, and C present the median value of RAD_A, RAD_B, and DF for each sequence and treatment, respectively. Panel D provides the results or linear regression analyses on RAD_A, RAD_B, and DF. Within Panel D, the independent variable, $ThescoreonriskattitudeSequence$, quantifies the average risk aversion level of each group, with a lower score indicating a higher degree of risk aversion. Robust standard errors, enclosed in parentheses, are clustered by group. In all panels, *, **, and *** indicate a significant difference from 0 at the 10, 5, and 1% significance levels, respectively.

Observation 3 *No treatment effect is discernible on RAD_B. Nevertheless, the value of RAD_B demonstrates a decreasing trend across sequences within both treatments.*

Observation 4 *The median DF is reduced in the W treatment in comparison to the WO treatment. Moreover, the value of DF demonstrates a declining trend across sequences within both treatments.*

Support:Panels A and B of Table 3 present RAD_A and RAD_B across each treatment and sequence, accompanied by comparative analyses. Panel C displays the median DF for each treatment and sequence, also facilitating comparisons between treatments. Panel D details the results from linear regression analyses applied to each metric.

Panel A reveals that the median RAD_A is statistically significantly higher in the WO treatment than in the W treatment. This difference is significant at the 5% level in Sequences 1 (0.026 in W vs. 0.111 in WO, $p = 0.047$) and 2 (0.025 in W vs. 0.074 in WO, $p = 0.015$), at the 1% level in Sequence 3 (0.023 in W vs. 0.112 in WO, $p = 0.002$), and at the 5% level across all sequences (0.023 in W vs. 0.103 in WO, $p = 0.015$), as determined by a one-sided Mann-Whitney test. These results suggest that restricting arbitrage opportunities increases the degree of mispricing of A-shares, which are characterized by relatively lower fundamentals. In contrast, Panel B shows no significant differences in the median RAD_B, indicating that restricting arbitrage does not affect the pricing of B-shares, which are characterized by relatively higher fundamentals.

Additionally, Panel C indicates that the median DF is statistically significantly higher in the WO treatment compared to the W treatment. This difference is significant at the 5% level in Sequence 1 (0.064 in W vs. 0.124 in WO, $p = 0.027$), at the 10% level in Sequence 2 (0.058 in W vs. 0.093 in WO, $p = 0.090$), at the 5% level in Sequence 3 (0.031 in W vs. 0.102 in WO, $p = 0.007$), and at the 5% level across all sequences (0.053 in W vs. 0.115 in WO, $p = 0.027$). These results suggest that constraining arbitrage opportunities increase the price deviations from fundamentals for the entire market.

The regression results in Panel D corroborate these findings. The "Treatment" independent variable shows a significant positive coefficient in the second column (for RAD_A) at a 10% significance level, and in the fourth column (for DF) at a 5% significance level. However, the coefficient in the third column (for RAD_B) is not significant. Furthermore, the "Sequence" independent variable exhibits a negative coefficient at a 5% significance level in the third and fourth columns, indicating a decrease in RAD_B and DF across sequences in both treatments. These results partially support **Hypothesis 2** and **Hypothesis 3**, and rejected **Hypothesis 0-2**.

Compared with the findings of Charness and Neugebauer (2019) regarding asset mispricing from fundamentals, our study identifies several divergences. Firstly, Charness and Neugebauer (2019) report that constrained risk-free arbitrage opportunities across shares are not linked to mispricing from fundamentals for the entire market. However, our results suggest that restricting arbitrage opportunities across shares may lead to significant mispricing relative to fundamentals. Secondly, Charness and Neugebauer (2019) proposes that the absence of risk-free arbitrage opportunities between different assets leads traders to overvalue shares with relatively higher fundamentals. Contrary to their findings, we did not observe such overvaluation in B-shares (also refer to the appendix A for details). However, our data suggest that constrained arbitrage opportunities between assets lead traders to significantly misprice assets with relatively lower fundamentals.

4.3 Further Analysis of Treatment Effects

In this subsection, we delve deeper into examining why limiting arbitrage opportunities results in a higher level of price discrepancy.

A possible explanation for such treatment effects may stem from the difference in the level of attention traders pay to the prices of twin shares. Specifically, in the WO treatment, where traders are restricted to transacting only one type of share, they may not pay attention to the prices of other share types when determining the value of the tradable shares. In contrast, in the W treatment, where traders have the ability to transact both types of shares, they may consistently reference the prices of the alternative share type when pricing a specific share type. If this explanation holds, the transaction price for each share type in the W treatment would be more significantly influenced by the most recent transaction price of the other share type prior to the transaction, compared to the WO treatment.

Observation 5 *In the W treatment, the deviation of transaction prices from the fundamental value of a specific type of shares statistically increases (decreases) when the most recent deviation of the other share type's price from its fundamental value rises (falls). However, this effect is not observed in the WO treatment.*

Support: Table 4 shows the regression results of the relative deviation of each transaction price of each type share from the fundamental.

In Panel A, the dependent variable, termed as "relative deviation in each trade of A-shares" is computed using the formula $\frac{P^{r,g}_{A,t,\tau}}{FV_{A,t}} - 1$, where $P^{r,g}_{A,t,\tau}$ represents the transaction price of an A-share at the τ-th transaction of period t, within sequence r of group g, and $FV_{A,t}$ signifies the fundamental value of each unit of A-share at period t. The independent variable, "Relate deviation of B-shares in the most recent transaction," is determined by $\frac{P^{r,g}_{B,t,\tau_A}}{FV_{B,t}} - 1$, where $P^{r,g}_{B,t,\tau_A}$ indicates the latest transaction

Table 4: Analysis of the relative deviation of each transaction's price of each type share from the fundamental.

Panel A. Regression analysis of the relative deviation in each trade of A-shares

Data set	*WO* treatment			*W* treatment		
Model	OLS 1	OLS 2	Random effect	OLS 1	OLS 2	Random effect
Independent variable	Coefficients					
Intercept	-0.076	-0.189	-0.112**	-0.033***	-0.031***	-0.032***
	(0.104)	(0.162)	(0.046)	(0.013)	(0.011)	(0.006)
Relate deviation of B-shares in the most recent transaction	-0.137	-0.038	0.042	0.290**	0.249**	0.267***
	(0.125)	(0.223)	(0.073)	(0.147)	(0.109)	(0.069)
Period number in session	-	0.010	-	-	-0.0003	-
		(0.006)			(0.0006)	
Interaction term	-	0.015	-	-	0.006	-
		(0.020)			(0.011)	
Adjusted R^2	0.002	0.050	0.004	0.179	0.179	0.158
Observations	884			790		

Panel B. Regression analysis of the relative deviation in each trade of B-shares

Data set	*WO* treatment			*W* treatment		
Model	OLS 1	OLS 2	Random effect	OLS 1	OLS 2	Random effect
Independent variable	Coefficients					
Intercept	-0.025	-0.055*	-0.038***	0.042***	0.044**	0.038***
	(0.022)	(0.032)	(0.011)	(0.015)	(0.176)	(0.006)
Relate deviation of A-shares in the most recent	-0.002	-0.030	-0.011	0.374***	0.418*	0.318***
	(0.046)	(0.041)	(0.037)	(0.123)	(0.236)	(0.070)
Period number in session	-	0.003**	-	-	-0.0002	-
		(0.001)			(0.0008)	
Interaction term	-	0.005**	-	-	-0.005	-
		(0.002)			(0.013)	
Adjusted R^2	-0.002	0.035	0.019	0.217	0.217	0.164
Observations	441			661		

Note: Robust standard errors in parentheses are clustered by session.
+: *, **, and *** indicate a significant difference from 0 at the 10, 5, and 1% significance levels, respectively.

price of a B-share prior to τ-th transaction of an A-share in the same period t, within sequence r of group g, and $FV_{B,t}$ denotes the fundamental value per unit of B-share at period t. The independent variable "Period number in session" represents the sequential period number across all three sequences, taking an integer value ranging from 1 to 30. The independent variable, "Interaction term" is the product of "Relative deviation of B-shares in the most recent transaction" and "Period number in session."

Similarly, in Panel B, the dependent variable, termed as "relative deviation in each trade of B-shares" is calculated using $\frac{P^{r,g}_{B,t,\tau}}{FV_{B,t}} - 1$, where $P^{r,g}_{B,t,\tau}$ represents the transaction price of an B-share at the τ-th transaction of period t, within sequence r of group g, and $FV_{B,t}$ signifies the fundamental value of each unit of B-share at period t. The independent variable, "Relative deviation of A-shares in the most recent transaction," is determined using $\frac{P^{r,g}_{A,t,\tau_B}}{FV_{A,t}} - 1$, where $P^{r,g}_{A,t,\tau_B}$ indicates the latest transaction price of a unit A-share prior to τ-th transaction of a unit of B-share in period t, within sequence r of group g, and $FV_{A,t}$ denotes the fundamental value per unit of B-share at period t. The independent variable, "Interaction term" is the product of "Relative deviation of A-shares in the most recent transaction" and "Period number in session."

In each panel, the regression outcomes presented in the second, third, and fourth columns derive from the dataset corresponding to the WO treatment, the fifth, sixth, and seventh columns originate from the dataset associated with the W treatment, respectively. Specifically, the second, third, fifth, and sixth columns in each panel present the linear regression outcomes employing the OLS model. In contrast, the fourth and seventh columns provide the panel analysis results utilizing the random effects model.

In Panel A of Table 4, the variable "Relative deviation of B-shares in the most recent transaction" demonstrates significant positive coefficients in the analyses conducted with the W treatment dataset. This is evident in both the OLS analysis, where it appears in the fifth and sixth columns at a 5% significance level, and in the panel analysis, noted in the seventh column at a 1% significance level. However, this variable does not hold any significant coefficients in the analyses conducted with the WO treatment.

Similarly, Panel B reveals comparable findings. The variable "Relative deviation of A-shares in the most recent transaction" exhibits significant positive coefficients in the analyses using the W treatment dataset, evident in both the OLS analysis (in the fifth and sixth columns at a 1% and 10% significance level, respectively) and the panel analysis (in the seventh column at a 1% significance level). Nonetheless, this variable does not show a significant effect in the analyses conducted with the WO treatment dataset.

These results indicate that in the W treatment, the pricing behavior of traders towards A-shares —- specifically, their propensity to overprice or underprice -— is influenced by recent pricing trends of B-shares, with a similar pattern observed in the opposite direction. This mutual pricing influence between A-shares and B-shares tends to result in a lower degree of price discrepancy within the W treatment, as well as reduced mispricing of A-shares when B-shares exhibit minor mispricing. In contrast, such a reciprocal pricing relationship is absent in the WO treatment. These findings support the explanation provided earlier in this subsection, suggesting that the ability to engage in transactions involving both share types encourages traders to consistently consider the pricing of one share type while determining the price of the other, thereby affecting their pricing decisions.

5 Conclusions

In this research, we conducted an experiment to explore how the absence of arbitrage opportunities across different assets affects assets pricing in a twin market. Our experimental design draws upon Charness and Neugebauer (2019), which in turn is grounded in the framework established by Smith et al. (1988). Prior experimental investigations into multi-asset markets have focused on the low of one price, analyzing price discrepancies by manipulating asset characteristics (Chan et al., 2013; Childs and Mestelman, 2006) and examining the interplay between future dividend processes (Charness and Neugebauer, 2019). Unlike these earlier studies, our research is, to our knowledge, the inaugural experimental inquiry to elucidate the impact of arbitrage opportunities between different assets on price discrepancies.

The experimental findings underscore the pivotal role of arbitrage opportunities across different assets, not only in achieving the law of one price but also in the pricing of assets relative to their fundamentals. Specifically, the data indicate that the lack of such arbitrage opportunities markedly exacerbates price discrepancies and the degree of deviation from fundamental values across the market.

Moreover, our data suggest that such effects stem from differences in the level of attention traders pay to twin share prices. When traders have the opportunity to arbitrage between different assets, they tend to focus more on the pricing of an alternate asset during transactions involving a specific asset, compared to situations where arbitrage is not possible. This reciprocal pricing influence between twin shares plays a crucial role in reducing both price discrepancies and fundamental mispricing in our experimental setup.

This finding does not contradict previous experimental results but rather provides an alternative perspective on those observations. For example, Charness and

Neugebauer (2019) noted a significant reduction in price discrepancies when the future dividend processes of assets were perfectly positively correlated, as opposed to when they were uncorrelated, which could be due to traders paying more attention to the pricing of other assets during transactions if the assets' future dividend processes are positively correlated.

It is noteworthy that our participants exhibited a much lower level of price discrepancies and deviations from fundamental values compared to other studies with similar experimental settings. Specifically, the degree of price discrepancy was approximately 50% of that reported by Charness and Neugebauer (2019) (see Appendix A) and only about 22% of the level found by Angerer et al. (2023)[8] under analogous conditions. Additionally, the degree of deviation from fundamentals (DF) was roughly 33% of that reported by Charness and Neugebauer (2019). This may be due to the fact that the participants in our experiment possess significantly higher cognitive abilities and are notably more prudent compared to the general Japanese adult population (Hanaki et al., 2024). These characteristics of our participants affirm the robustness of our results.

To align our study with others investigating multiple asset markets, we adopted the experimental framework of Smith et al. (1988), a common choice among similar studies. However, this setting does not inherently motivate traders to engage in transactions. As highlighted by Lei et al. (2001) and Crockett et al. (2019), the absence of transaction incentives can alter traders' pricing behaviors compared to scenarios where such incentives are present. Asparouhova et al. (2016) and Crockett et al. (2019) propose an alternative experimental framework for asset pricing where traders are incentivized to transact. This framework has been utilized to test the

[8] Angerer et al. (2023) employed a similar experimental setup to investigate how Arbitrage Robot Traders (ARTS) affect the law of one price across twin markets.

robustness of Lucas model features in a three-period cyclical world (Carbone et al., 2021) and to explore the impact of quantitative monetary easing policies on financial asset pricing (Duan and Hanaki, 2023). To the best of our knowledge, however, the framework of Asparouhova et al. (2016) and Crockett et al. (2019) has not yet been applied to investigate the low of one price or the underlying causes of price discrepancies, which presents a promising avenue for future research.

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A The analysis using the measures defined by Charness and Neugebauer (2019)

This section presents an analysis utilizing measures employed by Charness and Neugebauer (2019) and compares the findings between their study and ours.

The first measure is Δ_t, which is a relative difference from the parity pricing of the A-share and the B-share at each period, for a given group g in sequence r, it id defined as follows:

$$\Delta_t^{g,r} = \frac{P_{B,t}^{r,g}}{(P_{A,t}^{r,g} + (FV_{B,t} - FV_{A,t})} - 1 \tag{A.1}$$

where $P_{A,t}^{r,g}$ and $P_{B,t}^{r,g}$ represent the average transaction price of A-share and B-share in group g at period t, respectively, and $FV_{A,t}$ and $FV_{B,t}$ denote the fundamental value of A-share and B-share at period t, respectively. This ratio relates the value of the "unleveraged" company U to the value of the "leveraged" company L. In the equation, the difference between fundamental values shows the debt, $D_t = FV_{B,t} - FV_{A,t}$. The invariance theorem requires pricing at parity, $\Delta_t = 0$. In other word, market values differ by as much as but not more than fundamental values.

The second measure to be employed is to measure cross-asset price discrepancy, PD. For a given group g in sequence r, PD, is defined as follows:

$$PD^{g,r} = \frac{1}{T} \sum_{t=1}^{T} |\Delta_t^{g,r}| \tag{A.2}$$

The PD illustrates the extent of the price discrepancy, which signifies potential gains via selling high and buying low based on average prices. The PD is zero if the prices of A-share and B-share are equal to fundamental values or if the prices deviate from the fundamental values by the same magnitude.

The third measure utilized is the relative deviation (RD) for asset k (where $k = A, B$), calculated using the fundamental value of share k at period t, $FV_{k,t}$, and the average fundamental value of type k share, $\overline{FV}_k$. This measure is employed to quantify the magnitudes of bubbles within the experiment and has been similarly utilized in previous studies, such as that by, for example, Stöckl et al. (2010):

$$RD_k^{g,r} = \frac{1}{T} \sum_{t=1}^{T} \frac{P_{k,t}^{r,g} - FV_{k,t}}{\overline{FV}_k} \tag{A.3}$$

In contrast to the Relative Absolute Deviation (RAD), RD enables the determination of whether an asset is generally overpriced or underpriced. However, unlike RAD, it does not capture the fluctuation magnitude around the fundamental values.

The final measure employed is the Relative Absolute Deviation from fundamentals, denoted as DF, which was previously delineated in Subsection 3.1.

Table A.1 presents not only the average values of each measure and the comparison between treatments in our experiment but also includes the corresponding results from Charness and Neugebauer (2019) related to these metrics. It is pertinent to highlight that the configuration of the W treatment in our study closely mirrors the *Perfect Correlation* (PC) treatment described by Charness and Neugebauer (2019). The sole distinction between these treatments lies in the initial allocation of shares: in the W treatment, half of the traders are assigned 6 units of A-shares and the other half 3 units of B-shares at the start of each sequence, whereas in the PC treatment, every trader begins with 2 units of A-shares and 2 units of B-shares at the commencement of each sequence. Additionally, the only deviation of the *No Correlation* (NC) treatment from the PC treatment is that the future dividend processes of A-shares and B-shares are independent.

Table A.1: A comparative analysis of the results from Charness and Neugebauer (2019) and our study.

Data	Our study			Charness and Neugebauer (2019)		
Treatments	W (n=7)	WO (n=8)	W = WO	Perfect correlation (PC) (n=12)	No correlation (NC) (n=8)	PC = NC
Panal A. The average value of Δ						
Sequence 1	0.062	0.060	p = 0.768^{a}	0.070	0.277^{**c}	p = 0.031^{b}
Sequence 2	0.035	0.045	p = 0.478^{a}	0.017	0.299^{**c}	p = 0.001^{b}
Sequence 3	0.044	0.033	p = 0.567^{a}	0.035	0.179^{**c}	p = 0.165^{b}
Sequence 4	-	-	-	0.026	0.145^{**c}	p = 0.064^{b}
Total	0.047	0.046	p = 0.694^{a}	0.037	0.225^{**c}	p = 0.006^{b}
Panal B. The average value of PD						
Sequence 1	0.087	0.173	p = 0.047^{a}	0.229	0.398	p = 0.124^{b}
Sequence 2	0.065	0.102	p = 0.116^{a}	0.137	0.301	p = 0.014^{b}
Sequence 3	0.049	0.091	p = 0.060^{a}	0.138	0.233	p = 0.198^{b}
Sequence 4	-	-	-	0.151	0.204	p = 0.082^{b}
Total	0.067	0.122	p = 0.076^{a}	0.164	0.291	p = 0.082^{b}
Panal C. The average value of RD_A						
Sequence 1	0.004	-0.002	p = 0.694^{b}	0.028	0.002	-
Sequence 2	-0.010	-0.017	p = 0.955^{b}	-0.055	-0.050	-
Sequence 3	-0.007	-0.021	p = 0.955^{b}	-0.110^{**c}	-0.059	-
Sequence 4	-	-	-	0.037	-0.055	-
Total	-0.004	0.0002	p = 0.955^{b}	-0.025	-0.040	-
Panal D. The average value of RD_B						
Sequence 1	0.023^{*c}	0.019	p = 0.336^{b}	0.095	0.221^{**c}	-
Sequence 2	0.014	0.003	p = 0.779^{b}	-0.022	0.225^{***c}	-
Sequence 3	0.005	-0.005	p = 0.232^{b}	0.024	0.126^{**c}	-
Sequence 4	-	-	-	0.023	0.114^{**c}	-
Total	0.013	-0.004	p = 0.995^{b}	0.023	0.172^{**c}	-
Panal E. The average value of DF						
Sequence 1	0.089	0.151	p = 0.054^{b}	0.246	0.395	p = 0.320^{b}
Sequence 2	0.059	0.098	p = 0.189^{b}	0.153	0.304	p = 0.045^{b}
Sequence 3	0.043	0.107	p = 0.014^{b}	0.158	0.223	p = 0.320^{b}
Sequence 4	-	-	-	0.217	0.174	p = 0.758^{b}
Total	0.064	0.118	p = 0.054^{b}	0.193	0.274	p = 0.563^{b}

a: p-values are based on the one-tailed, two-sample Mann-Whitney tests. H_1: WO ¿ W.
b: p-values are based on the two-tailed, two-sample Mann-Whitney tests
c: In Panel A, C, and D, *, **, and *** indicate a significant difference from 0 at the 10, 5, and 1% significance levels, respectively. p-values are based on the two-tailed, one-sample Mann-Whitney tests. H_0: $RD_k = 0$.

Panels A and B present the mean values of Δ and PD for each sequence within each treatment. From Panel A, it is observable that in our experiment, Δ does not exhibit any statistically significant difference between the W and WO treatments, neither within individual sequences nor across all sequences. Furthermore, Δ does not statistically significantly differ from 0 in any sequence or across all sequences in either treatment, suggesting that no asset is consistently overpriced or underpriced irrespective of arbitrage opportunities.

These findings align with those from the PC treatment reported by Charness and Neugebauer (2019). However, in the NC treatment, the mean value of Δ is significantly greater than 0 across all sequences, at a minimum significance level of 5%, indicating a tendency for B-shares to be overpriced related to A-shares in the NC treatment. Additionally, the mean values of Δ in the NC treatment are statistically significantly higher than those in the PC treatment in Sequence 1, 2, 4, and across all sequences, at least at a 10% significance level.

In Panel B, the data from our experiment indicate that the mean values of PD are statistically significantly greater in the WO treatment compared to the W treatment in Sequence 1 and 3, as well as overall, at significance levels of 5%, 10%, and 10%, respectively.

These findings echo the outcomes for LPD presented in Section 3.1, albeit with larger p-values. This difference occurs because PD tends to underestimate scenarios where A-shares are overpriced relative to B-shares. Furthermore, the data of Charness and Neugebauer (2019) shows a significant difference on average PD between PC and NC treatments, which supports that a perfect positive correlation between shares' future dividend process may decline the price discrepancy compared to when future dividend process of shares are uncorrelated.

When compared to the findings of Charness and Neugebauer (2019), our data exhibits lower average values of PD; particularly noteworthy is that the average PD values for the W treatment are less than half of those for the PC treatment, despite the near-identical settings of these treatments. This difference can be attributed to our experiment's average Δ values having a lower variance, indicating a narrower fluctuation range around 0, compared to the results reported by Charness and Neugebauer (2019).

Panels C and D display the mean values of RD for A-shares and B-shares, respectively, across each sequence within each treatment. In Panel C, no significant differences are noted in the average values of RD_A between the treatments of each study, nor between the average values of RD_A and 0, with the exception of Sequence 3 in the PC treatment. The majority of the average values of RD_A fall within the range of -0.1 to 0.1. Panel D documents a similar pattern for the mean values of RD_B across the W, WO, and PC treatments, indicating that the mean values of RD_B of these treatments fall within the -0.1 to 0.1 range and are not statistically significantly different from 0.The only exception is the average RD_B in Sequence 2 of the W treatment (= 0.023), which is significantly higher than zero at the 10% significance level. In contrast, within the NC treatment, the mean values of RD_B significantly exceed 0 across all four sequences. This observation implies that in scenarios where the future dividend processes of shares are uncorrelated, traders might be predisposed to assign a higher value to shares with comparatively higher fundamentals. This treatment effect was not observed in our experiment.

Panel E outlines the mean DF values in each sequence for each treatment. As delineated in Section 4.2, our experiment identified significant differences in mean DF values between the W and WO treatments in Sequences 1 and 3, and overall. This indicates that the lack of arbitrage opportunities across different shares amplifies the extent of mispricing from fundamentals, suggesting that the difference in the degree of price discrepancies between treatments correlates with the degree of mispricing from fundamentals. Contrary to our findings, the data from Charness and Neugebauer (2019) do not indicate any discrepancies between the PC and NC treatments, leading to the conclusion that the variation in price discrepancy degrees between treatments does not stem from fundamental mispricing. Moreover, compared to the results from Charness and Neugebauer (2019), our data demonstrates a reduced level of mean PD values across all sequences and treatments, signifying that traders in our experiment priced shares more closely to fundamentals than those in the study by Charness and Neugebauer (2019).