# Behavioral Mis-pricing and Arbitrage in Experimental Asset Markets*

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Abstract

I document the effects of a particularly robust behavioral "purchasing bias" on experimental asset market outcomes. As argued by behavioral finance, such biases can affect markets, here pushing prices above no-arbitrage bounds. Interestingly, relative prices remain largely unaffected. By comparing experimental markets with and without active arbitragers, I provide evidence on a behavioral finance counter-argument: that arbitragers will drive biases out of existence. I find that, while it *is* possible, it is unlikely that a profit maximizing arbitrager will completely drive out biases. Active arbitrage also increases volume and volatility while decreasing relative price efficiency and market risk sharing efficiency.

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## I. Introduction

One of the foundations of research in behavioral finance is the observation that human beings are prone to a host of biases and often make what appear to be outright mistakes relative to "optimal" economic behavior (e.g., Kahneman, and Tversky, 1979). A reasonable inference is that, based on these biases, investors and traders in financial markets will behave in ways not predicted by traditional financial theory. Further, if many or most traders are prone to particular biases, then asset prices and allocations will be affected by them (e.g., Daniel, Hirshleifer and Subrahmanyam, 2001, and much of the research cited in Daniel, Hirshleifer and Teohc, 2002, make this argument). I will refer to the aggregate price effects of behavioral biases as "behavioral mis-pricing."

Considerable evidence suggests that traders do buy, sell and hold investments for "irrational" reasons predicted by behavioral biases and mistakes (e.g., Barber and Odean, 2001, and much of the research discussed in Nofsinger, 2002). That markets are affected and traders may be hurt by these irrationalities seems to be the logical conclusion. However, simple counter arguments and some evidence suggest the link to this conclusion is not as straightforward as it first appears. The simplest counter argument is that, in a market, it only takes a few rational traders to drive prices to efficient levels. In particular, if the biases cause violations of arbitrage relationships, they should be countered quickly.[1]

Here, I document a pervasive endowment based "purchasing bias" that drives up prices in experimental asset markets. Left alone, traders never drive out the effect of this bias on aggregate prices even though it violates no-arbitrage restrictions. It gives me the opportunity to study whether we can reasonably expect arbitragers to drive out behavioral mis-pricing in a controlled environment.

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[1] Other arguments and evidence against this conclusion include, but are not limited to: (1) that market structure (e.g., Gode and Sunder, 1992 and 1993) or market structure combined with self-selected roles (e.g., Oliven and Rietz, 2004) may help force efficient prices, (2) that biased traders may stop trading or losses may prevent then from trading further and, after that point, they stop affecting market prices (e.g., Forsythe, Rietz and Ross, 1999) or (3) that biased trader may learn optimizing behavior (e.g., Berg, Dickhaut and O'Brien (1985) show that exploiting arbitrage opportunities helps extinguish sub-optimal behavior in preference reversals).

The experimental asset markets run for this study are simple. Subjects trade two Arrow-Debreu state contingent claims that span the outcome space. At the end of a market period, one or the other will pay a dividend of $0.50 or, in terms of the experimental currency, 1,000 "francs." Payoff probabilities are known. The portfolio of both claims always pays 1,000 francs. This creates an arbitrage restriction on prices: they should sum to 1,000. Subjects trade these assets in repeated identical market periods organized as oral double auctions. In each period, the aggregate quantities of the two claims are equal. Because of this, traditional theory predicts expected value pricing regardless of risk preferences.[2]

In the markets run for this paper, the subjects regularly price both assets above expected values and the arbitrage restriction on prices is nearly always violated. The relative overpricing is approximately the same across claims. As a result relative prices are closer to predictions than absolute prices. These results are very robust. Several treatments rule out various explanations of this overpricing result. I conclude that it is simply a bias of subjects in these particular markets to purchase assets on average that drives up prices (a "purchasing bias"). A final experimental session designed to test this conjecture gives evidence consistent with it.

The primary question of this paper is whether an arbitrager can drive out the behavioral mis-pricing. To test it, I ran a treatment where the experimenter acts as the arbitrager and exploits every profitable arbitrage opportunity that arises. In fact, an arbitrager can drive nearly arbitrage-free pricing. However, to do so, the arbitrager must dominate the market and participate in the majority of trades, volume skyrockets, volatility increases and, if anything, relative prices are driven out of line. Analysis of arbitrager profits shows that exploiting every opportunity is sub-optimal for the arbitrager. A clearly better strategy would be for the arbitrager to allow some deviation in prices away from no-arbitrage bounds. This represents the limits of arbitrage as discussed by Shleifer and Vishny (1997). The overall conclusion is that arbitragers may help mitigate behavioral mis-pricing relative to an arbitrage bound.

[2] See Appendix I.

However, unless they have sufficient total resources and are sufficiently competitive, arbitragers are unlikely to make the effects of pervasive biases disappear completely.

The results have implications for several areas in finance. Consistent with behavioral finance arguments, the results show that traders' behavioral anomalies can create significant, robust biases in absolute prices. These biases may not be driven out of existence naturally by arbitragers. This has welfare implications: it hurts traders most prone to the bias. The results add evidence to the debate over the effects of arbitragers. While they drive prices toward no arbitrage bounds, arbitragers also increase volume and volatility while inhibiting the relative pricing and risk sharing efficiencies of the markets. The absolute and relative pricing results have implications for asset pricing in general. Here, the behavioral bias affects absolute prices, which would challenge models based on absolute prices or returns (e.g., CAPM). Relative prices are closer to predictions, which would allow models based on relative prices or returns (e.g., APT) to retain more validity. This is consistent with evidence in O’Brien and Srivastava (1991). The results also have implications for research on prediction markets (see Berg, Forsythe, Nelson and Rietz, 2003; and Wolfers and Zitzewitz, 2004). The relative pricing efficiency here supports the common practice of focusing only on relative prices through “normalization” (dividing individual contingent claim prices by the sum of prices for claims spanning the entire space of outcomes).

Many researchers have studied asset pricing predictions in experimental markets (see Sunder, 1995). The design of the experiments in this paper differ from most prior research in experimental asset markets because of the simple claim structure, the arbitrage relationships it sets up and the implications these have for asset pricing.[3] Several prior studies focus on arbitrage relationships. O'Brien and

[3] Many competitive asset market experiments have involved informational conditions under which uncertainty could be resolved by the markets. That is, while no individuals have enough information to determine the state, the market's information (the union of all individuals' information) is sufficient to determine the state and, hence, the value of assets. For examples see Forsythe, Palfrey and Plott (1982), Plott and Sunder (1982 and 1988) and Forsythe and Lundholm (1990). In equilibrium, these markets can resolve all uncertainty about asset values. If the uncertainty is indeed resolved, it makes pricing trivial: prices will equal true claim values. Prior experimental markets without sufficient information to determine asset values exactly seldom have complete sets of contingent claims. For example, see Smith, Suchanek and Williams (1988) and O'Brien (1988). As shown in the appendix, this aspect of the experimental design drives the clear prediction here of expected value pricing independent of risk preferences.

Srivastava (1991) study arbitrage relationships in relative prices. However, they use an information structure sufficient to determine the state and the absolute values of assets. They do not study simple arbitrage restrictions on absolute prices with unresolvable uncertainty nor do they study the effects an active arbitrager would have on their markets. Here, mirroring their results, very few arbitrage opportunities arise in relative prices. However, new results here show that opportunities regularly arise in absolute prices and an active outside arbitrager has a profound effect on the markets.

The contracts and markets here are similar in structure to those traded in "winner-takes-all" prediction markets run on the Iowa Electronic Markets (IEM, for short; see Berg, Forsythe, Nelson and Rietz, 2003). Oliven and Rietz (2004) study arbitrage violations on the IEM. Their work shows that arbitrage violations frequently appear in the IEM, but are driven out quickly. There are three important differences between the current paper and research with the IEM. First, here the state probabilities are known by the experimenter (and all traders). As a result, pricing efficiency can be tested directly. Second, arbitrage violations appear regularly here and no traders exploit them except in a treatment where the experimenter takes on the role of arbitrager and exploits all profitable opportunities. This allows a comparison of markets with and without an active arbitrageur. This type of experimental comparison cannot be conducted in field markets (such as the IEM) or naturally occurring markets. Third, the laboratory environment allows controlled replication and comparisons across treatments.

The most closely related papers to this one are Forsythe, Rietz and Ross (1999) and Weber, Keppe and Myer-Delius (2000). Forsythe, Rietz and Ross (1999) contains a brief discussion of three of the markets included in this paper (the OPIS design discussed later) and adds a treatment to test a specific hypothesis about trader expectations and behavior in prediction markets. Weber, Keppe and Myer-Delius (2000) replicate the results of previous versions of this paper on German students trading in computerized markets. They add a treatment to test a specific hypothesis about framing and endowments. Their paper complements this paper by showing the results are robust to several design changes. The focus of this paper differs considerably. Here, I focus on a simple question left unaddressed by the prior research:

Can we expect arbitragers to force absolute prices to efficient levels in the face of a robust behavioral mis-pricing? The answer is "yes," but not without considerable effort and adverse impacts on market volumes, volatilities, relative prices and the risk sharing efficiencies of the markets.

In the next section, I lay out the experimental design. Formal pricing relationships for the claims traded are developed in Appendix I for the interested reader. Section III gives the results and the last section concludes with discussion. Appendix II gives the experimental instructions.

## II. Experimental Design

### A. Common Design Characteristics

With one exception (due to time constraints) each experiment consisted of fifteen sessions.[4] Table I summarizes the design and treatment features. Here, I discuss the features common to all treatments. Then, I discuss treatment specific features and preview the results for each treatment. Subjects came from a large volunteer subject pool of M.B.A. and undergraduate students recruited from classes at the University of Iowa. Each cohort of 10 subjects participated in only one treatment, with the exception of session OPI-5(e), which used experienced subjects.[5] In each session, subjects participated in a series of 15 oral double auction asset market periods lasting 5 to 7 minutes (see footnote 4). Each session lasted two and one half to three hours.[6] Subjects earned an average of $30.00 each.

Upon arrival, subjects sat apart from each other in a classroom and received copies of the instructions and their own information and record sheets. (Appendix II contains these instructions.) After all subjects had arrived, the experimenter read the instructions aloud and answered any questions, making the instructional information commonly known. Except to make bids, offers and acceptances, subjects could not speak to each other. They could ask the experimenter questions at any time.

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[4] Session OPI-5(e) ran for 13 periods.

[5] This avoids hysteresis affects that may arise when switching between treatments within a cohort.

[6] Subjects were recruited for three hours. Session OPIA-2 ran somewhat longer than three hours with the consent of all subjects.

In each period, subjects participated in at least two simultaneous oral double auction markets with all bids, offers and acceptances publicly recorded. They used "francs" for currency in the markets. Each franc earned was worth $0.0005 at the end of the experiment. Subjects could not make short sales except under a treatment labeled OPIS (discussed later). In these markets, subjects traded units of two contingent claim assets ("Green Certificates" and "Blue Certificates") separately. Subjects could make bids or offers in any market at any time. They could also accept bids or offers in any market or all markets simultaneously. (Thus, they could exploit arbitrage opportunities without execution risk.)

At the end of each market period, trading ceased and a random draw determined the "state." Specifically, without looking, a subject drew a marble from a bucket containing 6 blue marbles and 14 green marbles of identical size. Subjects knew in advance how many marbles were of each color. The color of the drawn marble (shown to all subjects except in session OPI-6(r) discussed below) determined the state: either "Blue" or "Green." The subject returned the marble to the bucket after determining the state. In the Blue state, each Blue certificate paid its owner 1,000 francs (50 cents), while Green certificates paid 0. In the Green state, each Green certificate paid its owner 1,000 francs, while Blue certificates paid 0. The total numbers of Blue and Green certificates were equal, resulting in fixed aggregate payoffs. As Appendix I shows, this leads to the price predictions of 300 francs for Blue certificates and 700 francs for Green certificates regardless of risk preferences and obvious arbitrage restrictions on the sum of certificate prices.

At the beginning of each period, subjects received initial endowments of francs on hand and inventories of Blue and Green certificates. Subjects knew their initial endowments for all periods at the beginning of the session. Subjects began each period with 40,000 francs that they could use for trading.[7] This cash was subtracted at the end of the period as a fixed cost. Subjects also began each period with unequal numbers of the two certificate types. Unless subjects were risk neutral, these were not Pareto

[7] At equilibrium prices, this is enough currency to buy all the endowed certificates in a period. Though prices often exceeded predictions, subjects never had binding liquidity constraints.

optimal distributions. Hence, there were incentives for trade between non-risk neutral subjects.[8] Each period, subjects alternated between holding a portfolio of two Blue and six Green certificates and a portfolio of six Blue and two Green certificates. Five subjects began each period holding each type of portfolio.[9] Subjects were endowed with a total of forty Blue certificates and forty Green certificates.

B. Treatments

1. The Baseline Treatments: OPI, OPI(e), OPI(m) and OPI(r)

The OPI (Oral double auction with Private Information about endowments) treatment is the baseline. Under this treatment, subjects could not short sell. Each initial endowment effectively included two "unit portfolios" consisting of one Blue and one Green certificate, which paid exactly 1,000 francs regardless of the state. Though subjects could not trade directly in the unit portfolio, they could accept bids or offers in both markets simultaneously. Hence, when the sum of bids across markets exceeded 1,000 francs or the sum of offers fell short of 1,000 francs, subjects could exploit the resulting arbitrage opportunity without any execution risk. In spite of this, prices were uniformly high, creating hundreds of unexploited arbitrage opportunities.

The OPI(m) treatment shows that the arbitrage opportunities did not arise because of subjects misunderstanding the profitability of arbitrage opportunities. It was the same as the OPI treatment except for two modifications in the instructions. First, the dividend tables contained an extra row that was explained in the text. This explained how the dividend to a "unit portfolio" consisting of one of each certificate type would always be 1,000 francs regardless of the marble drawn. Second, subjects received additional instructions between periods 8 and 9. These explained how selling one of each certificate type at prices that totaled more than 1,000 francs always resulted in a certain profit. Similarly, they explained

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[8] Risk averse subjects will want to hold equal quantities of the two certificate types to insure themselves against risk. Risk seeking subjects will want all of their certificates to be of one type to maximize their risk. Risk neutral subjects will be indifferent between holding certificates or buying and selling them at equilibrium prices.

[9] A total of 10 subjects, 5 with each endowment type, should be sufficient for competitive outcomes. See Smith, Williams, Bratton and Vannoni (1982).

how buying one of each certificate type at prices that totaled less than 1,000 francs always resulted in a certain profit. This did not decrease prices.

The OPI(e) treatment shows that the arbitrage opportunities did not arise because of subject inexperience. In this treatment, subjects were experienced, having participated in one previous session for this paper. Further, all subjects in this treatment knew that all other subjects had participated in exactly one previous session. The session only ran for 13 periods because of one subject's time constraint. In all other respects, the OPI(e) treatment was the same as the OPI treatment. While, Smith, Suchanek and Williams (1988) show that after one or two replications price bubbles appear less robust and often disappear in their experiments, it is not the case here. In this design, each period is a replication. After two sessions and 28 replications, overpricing remained.

The OPI(r) treatment shows that the arbitrage opportunities did not arise because of anticipation or excitement surrounding the marble draw. This might cause subjects to focus their attention on a single certificate type and "bet up" its price in hopes of a big win resulting from the marble draw. In this treatment, feedback was restricted. Marble draws were not revealed to subjects. Instead a subject monitor was paid to observe payoff determining draws and calculate each subject's winnings. At the end of the experiments, subjects were paid based on their total profits. This should remove any "thrill" of gambling that may be associated with seeing the marble draw. Again, this did not eliminate overpricing.

2. The Direct Portfolio Trading Treatment: OPIP

To exploit arbitrage opportunities and recognize unexplainably high prices, subjects must be aware of the nature of the two-asset portfolio. OPI-4(m) adds a detailed explanation to no avail. Treatment OPIP attempts to highlight the portfolio nature of the assets by allowing direct Portfolio trading. Subjects could trade the unit portfolio directly in a third market called "Both." Subjects could sell separately purchased certificates as a unit portfolio in this market. Similarly, subjects could buy certificates as a unit portfolio in this market and trade them in separate markets later. Each initial endowment effectively included two unit portfolios. Subjects could accept bids or offers in any two or all three markets simultaneously. This produces a second form of arbitrage restriction, between the Blue and Green certificate prices and the portfolio market price. While this does not constitute short selling, subjects could cycle portfolios through the arbitrage opportunities created if certificate prices remained high and portfolios were properly priced.

Subjects seemed aware of the nature of the portfolio. While portfolio volume was low (averaging 25 direct portfolio transactions versus 265 individual certificate transactions on average per session), many subjects placed portfolio bids and asks and traded portfolios along with individual certificates. Portfolio prices tracked the summed individual certificate prices. This design met with limited success in eliminating overpricing. Summed prices held near their predicted values for part of session OPIP-3.

3. The Short Sale Treatment: OPIS

To take advantage of the arbitrage opportunities, traders in the market may need to sell short. The OPIS treatment added a controlled form of Short sales to the OPI treatment.[10] Again, each initial endowment effectively included two unit portfolios. In addition, subjects could effectively sell certificates short under this treatment. Through short selling, subjects could make arbitrage profits by simply accepting both the Blue and Green bids any time they summed to more than 1,000 francs. Later, they would purchase the "short" portfolio from the experimenter for the guaranteed price of 1,000 francs. If subjects recognized the opportunity, this effectively created a perfectly elastic supply of unit portfolios at a price of 1,000. Allowing short sales did little to decrease prices. No subjects stepped forward to become arbitragers. Traders were hesitant to short sell and volumes actually fell in these markets.

[10] Specifically, during trading, individual inventories could fall below zero. At the end of trading, subjects had to "purchase" enough unit portfolios from the experimenter to bring their inventories of both certificate types up to zero. For each unit portfolio purchased, they had to pay 1,000 francs. They received this 1,000 francs back as a dividend if the certificate type they did not sell short paid a dividend. They lost this 1,000 francs if the certificate type they sold short paid a dividend. In this way, allowing negative inventories and then requiring the unit portfolio purchases is equivalent to short selling.

4. The Arbitrager Treatment: OPIA

This treatment effectively introduced an arbitrager into the market. It was identical to the baseline treatment OPI with one exception. Instead of relying on subjects to exploit arbitrage opportunities that arose, the experimenter enforced the arbitrage restrictions directly. The instructions stated:

> "The experimenters will participate directly in the markets in the following manner and only in the following manner. If there are bids outstanding for both certificates and these bids sum to more than 1,000 francs, the experimenters will accept both bids. That is, if the experimenters can sell one of each certificate type simultaneously for a total that exceeds 1,000 francs, they will do so. (The experimenters' trader ID number will be zero.) Similarly, if there are two offers outstanding and these offers sum to less than 1,000 francs, the experimenters will accept both offers. That is, if the experimenters can buy one of each certificate type simultaneously for a total of less than 1,000 francs, they will do so. These are the only times that the experimenters will participate directly in the market."

With three unnoticed and unintentional exceptions, the experimenter did take both bids whenever they totaled 1,001 francs or more and both offers whenever they totaled 999 francs or less. (Generally, the subjects themselves pointed out the profitable arbitrage opportunities to the experimenter, leaving little room for experimenter error.) This effectively created a perfectly elastic supply of unit portfolios at a price of 1,001 and an infinitely elastic demand at the price of 999 francs. Prices did drop under the OPIA treatment, but the frequency of violations remained high, volumes skyrocketed and relative prices were driven away from their predicted values.

## III. Results

The two main purposes of this paper are to (1) document the existence of behavioral mis-pricing in these markets and (2) ask whether an arbitrager can drive this mis-pricing out of existence. I present each of the two main results in a subsection followed by subsidiary results. In brief, in the absence of an arbitrager, prices are uniformly high reflecting robust behavioral mis-pricing. The generally high prices results in many profitable, unexploited arbitrage opportunities. Relative prices are closer to predictions than absolute prices. An arbitrager can drive behavioral mis-pricing out of absolute prices. But, this is not without cost. It takes a great deal of effort from the arbitrager, increases volume and volatility, reduces the risk sharing efficiency of the markets and, if anything, drives relative prices out of line.

A. Results on Behavioral Mis-Pricing

**Result 1: Behavioral Mis-Pricing Drives Up Absolute Prices**

Figure 1 shows the prices and volumes from all sessions. The bars give the contract volumes (scaled to the right-hand axis). The top three solid lines give predictions for Blue prices (at 300), Green prices (at 700) and the summed prices (at 1,000). The lowest solid line gives the minimum volume necessary for efficient risk sharing (which will be discussed later). Lines with symbols give average Blue and Green trade prices (with two standard deviation ranges shown by light dashed lines) and the sum of these average prices. The sum of average (within a period) blue and green prices averaged (across periods) is 1,242 in the baseline treatments, 1,184 in the short-sale treatments and 1,137 in the direct portfolio treatments. During the last five periods of sessions in each treatment, the averages were 1,201, 1,183 and 1,145, respectively. Thus, certificates were overpriced in aggregate by 14.5% to more than 20% on average.

Figure 1 shows clearly that, with few exceptions, summed absolute prices exceeded predictions in all treatments except the arbitrage treatment. To test for differences from predictions, I use two-sided t-tests based on log-normal distributions of prices (prices cannot fall below zero) and the null of an average price of 300 for Blue and 700 for Green certificates. In the baseline sessions, Blue prices significantly exceeded the prediction of 300 in 85% of the periods in which the statistic can be calculated.[11] Green prices significantly exceeded 700 in 94% of the periods. In the short sale sessions, Blue and Green prices significantly exceeded predictions in 62% and 89% of the periods, respectively. For the portfolio trading sessions, prices exceeded predictions in 84% and 68% of the periods, respectively. Overall, prices exceeded predictions significantly during 83% of the certificate-periods in the non-arbitrage sessions.

[11] It cannot be calculated if there is no trade or if the observed standard deviation is zero.

The generally high prices led to frequent arbitrage opportunities between the prices available for simultaneous certificate sales (the sum of the bids) and the known final value of the two-certificate portfolio (1,000 francs). Table II summarizes these arbitrage opportunities. It lists the number of events in each session and the fractions of events that were not trades.[12] It also lists the number of times bids or offers were outstanding simultaneously in the Blue and Green markets and the number of these events that represented arbitrage opportunities. Finally, it shows the average size of the arbitrage opportunities available in each session. With the exception of the arbitrage treatment sessions, the behavioral mis-pricing causes a large number of quite profitable, unexploited arbitrage opportunities.

**Result 1.1: Relative Prices are Tied More Closely to State Probabilities than Absolute Prices**

As discussed in Appendix I, theory implies expected value pricing in these markets. However, prices generally lie above expected values. Nevertheless, relative prices may still reflect relative state probabilities. Relative prices should equal 0.3/0.7 = 0.4286. Alternatively, one can normalize prices by dividing each price by the average sum of prices in each period. Thus, for Blue, the normalized price ($1{,}000 \mathrm{x} P^B/(P^B+P^G)$) should equal 300. For Green, the normalized price ($1{,}000 \mathrm{x} P^G/(P^B+P^G)$) should equal 700. Normalized prices depend only on relative prices.

Analysis of relative and absolute price levels for all sessions and treatments gives interesting results. Consider a binomial variable that takes on the values of 0 if absolute prices were closer to predictions and 1 if normalized (relative) prices were closer to predictions according to deviations from predictions summed across the two contracts each period. Prices were closer to the relative prediction than the absolute predictions in 99% (all but one) of the periods in the baseline sessions, in 86% (all but 6) of the periods of the OPIS sessions and 93% (all but two) of the periods in the first two OPIP sessions. In all of these sessions, relative pricing predictions fit the data significantly better than absolute prices

[12] A transaction would eliminate any arbitrage opportunity that existed

according to binomial statistics.[13] In later periods of the OPIP-3 and the OPIA sessions, absolute prices were driven down toward no arbitrage levels and normalization makes little difference. Similar results are obtained by asking whether the log price ratio (to be consistent with the assumed log normal distribution) differs from the prediction of ln(300/700). The overall rejection rate for non-arbitrage sessions is lower than the rejection rate on absolute prices (72% of the time for relative prices versus 83% of the time for absolute prices). Further, unlike the results for absolute prices, the rejections are not uniformly on one side (50% are in one direction and 22% the other).

The overall result is that, while relative prices do not always match predictions, they are remarkably closer to predictions than absolute prices on average. This has an interesting implication for prediction markets such as the IEM. If the same pricing pattern holds there, then the common practice of normalizing prices helps improve the predictive accuracy of the markets.

**Result 1.2: Behavioral Mis-Pricing Does Not Lead to Inter-Market Arbitrage Opportunities**

In sessions with direct portfolio trading (OPIP), there was a second arbitrage opportunity based on relative prices of the two individual claims and the price of the portfolio in the direct portfolio market. Table III summarizes these arbitrage opportunities. Inter-market arbitrage opportunities seldom occurred. In surprising contrast to the frequency of arbitrage between the certificate prices and the final payoffs discussed, only nine arbitrage opportunities arose between direct portfolio prices and individual certificate prices. Thus, subjects were able to avoid violating arbitrage restrictions on relative prices. Portfolio prices tracked the summed individual certificate prices, though both were higher than predicted in

[13] All but one of the statistics are significant at the 1% level of confidence and the last is significant at the 10% level of confidence in one sided tests on an experiment by experiment basis. At first, one might expect normalizing will give the relative pricing predictions an advantage. However, this is generally not the case. If the arbitrage restriction holds, normalization with have no effect. If one claim price exceeds the prediction on average while the other falls below the prediction, normalization will always make one relative price fit better and one fit worse than the absolute. Similarly, of both prices fall above or below predictions, but the error for one claim is much larger than the other, normalization could make one relative price fit better and the other fit worse than the absolute. Only if both prices exceed or fall short of the predictions and the errors are of the same order of magnitude will normalization make both relative prices fit better.

absolute terms. Again, the results are consistent with efficient relative pricing in spite of deviations in absolute prices from predictions. This is consistent with O'Brien and Srivastava's (1991) results that there are few arbitrage opportunities in relative prices.

**Result 1.3: Traders Who Buy are Hurt by the Bias in Absolute Prices While Those Who Sell Gain**

Who gains and loses from the mis-pricing? The absolute level of overpricing must come from predominant tendencies to buy instead of sell in these markets. I analyze who profits and who loses on an aggregate basis by dividing the traders up into self-determined roles according to their trading behavior.[14] Define an overall buyer is a trader who, relative to his or her endowment, ends a period with at least as many of both certificate types and at least one more of a given certificate type. Sellers are defined in the opposite manner. Other traders either did nothing net or ended up with fewer of one certificate type and more of the other. Analyzing profits across these trader types tells how much traders with tendencies to buy lost and how much traders with tendencies to sell gained as a result of the behavioral mis-pricing.

Table IV shows the average trading profits (defined as the difference between the expected value of the endowment and expected value of the final portfolio) for traders defined as buyers, sellers and others. Across all treatments, the behavior of buyers reduced the expected value of their portfolios significantly. Sellers gained significantly. Other traders neither gained nor lost on average.

Similar results hold if the analysis is on a trade-by-trade basis. Averaging across all of the treatments except the arbitrage treatment, the average wealth transfer from buyers to sellers was 92 francs for blue certificates. This works out to about 1/3 of the certificate's expected value. For green certificates, the average wealth transfer was 105 francs or about 1/7 of the certificate's expected value. The average total transfer from buyers to sellers was 23,762 francs per session.

[14] The idea that role choice may affect financial markets and trader profits goes back at least to Working (1958) and, in its modern form, serves as the basis for market micro-structure models (e.g., Kyle, 1985).

B. Results on the Effects of Arbitrage Exploitation

**Result 2: An Active Arbitrager Can Reduce the Effects of Behavioral Mis-Pricing on Aggregate Absolute Price Levels**

Figure 1 shows that the arbitrager drove the sum of absolute prices toward the no arbitrage level of 1,000 francs in the OPIA treatment sessions. In the baseline sessions, the sum of the average blue and green certificate prices averaged 1,242 over all periods and 1,201 over the last five periods of each session. In the arbitrage sessions prices averaged 1,049 and 1,015 over the respective sets of periods. Difference-in-means t-tests (treating each period as an observation) are 10.83 ($p<0.0001$) overall and 9.99 ($p<0.0001$) over the last 5 periods of each session. Rank sum tests give similar results. Similar statistics show that prices in the arbitrage treatments were significantly lower than each other treatment. Prices also fell somewhat in the portfolio sessions relative to the baseline.

Interestingly, while prices fell dramatically under treatment OPIA, the frequency of arbitrage opportunities did not change significantly. According to two-sample Wilcoxon tests (using each session as an observation), no treatment appears significantly different (from all other treatments combined) in the percentage of arbitrage opportunities observed on the bid side.[15] While the frequency of arbitrage opportunities differed little, their nature changed dramatically across treatments. According to two-sample Wilcoxon tests (using each session as an observation), the opportunities in OPIA sessions were significantly smaller in size (z=2.598, p-value=0.009) than in the other sessions. The average size was an order of magnitude smaller (15.97 francs in the OPIA sessions versus 152.89 in the other sessions combined). There were no other significant differences for individual treatments.

Therefore, active arbitrage can drive out the absolute behavioral mis-pricing. However, it is not without cost.

[15] Only sessions in the OPIP treatment produced any arbitrage opportunities on the ask side (with 3 total opportunities). According to a matched sample (by session) rank sum test, opportunities in bids appear significantly more often than those in asks (z=3.048, p-value=0.001).

**Result 2.1: An Active Arbitrager does not Improve Efficiency of Individual Asset Prices and Decreases Relative Price Efficiency**

While the arbitrager reduced the size of arbitrage opportunities and drove the sum of prices down toward the no arbitrage bounds, individual certificate price efficiency was not improved and relative prices were driven out of line. In the arbitrage sessions, Blue prices deviated significantly from predictions 98% of the time and Green prices deviated significantly from predictions 76% of the time for a grand average of 87% (compared to 83% for the non-arbitrage treatments). How can this be? It can be seen in Figure 1. In session OPIA-1 Blue prices were driven significantly (according to t-tests) below predictions while Green prices stayed significantly above. In the other two sessions, Green prices were driven significantly below predictions and Blue prices stayed significantly above. As a result, relative prices differed significantly from predictions 95% of the time. Thus, a cost of forcing aggregate prices down to the no-arbitrage limit is that it biases relative prices.

**Result 2.2: An Active Arbitrager Causes Volumes to Skyrocket**

Figure 1 shows the volumes in each market in each period of each session. Volume in the six baseline sessions averaged 19.4 transactions per period. In the direct portfolio trading sessions, the average Blue and Green volume was 17.7 certificates, just smaller than the baseline. Portfolio volumes averaged 1.7 portfolios per period. In the sessions allowing short sales, volume actually fell to an average of 11.9 trades per period. The overall average volume from all sessions without an arbitrager was 16.4 trades per period. Introducing the arbitrager doubled volume to an average of 32.7 trades per period in the OPIA sessions. This difference is significant (with a two-sample Wilcoxon statistic of 2.598 (p-value=0.009) treating each session as an observation). In contrast, in the OPIS sessions, volumes fell significantly (with a two-sample Wilcoxon statistic of 2.598 and p-value=0.009). There were no other significant inter-treatment differences. The implication is that, in order to drive absolute pricing efficiency, the arbitrager must be extremely liquid and active.

**Result 2.3: An Active Arbitrager Increases Price Volatility**

One concern of regulators is that arbitrage and program trading cause excess price volatility.[16] Figure 1 gives two standard deviation ranges around prices each period. Volatility was quite low in the latter parts of all sessions, often approaching zero. To measure volatility, I use the average intra-period standard deviation of prices for the whole session and for the last five periods of each session (to control for the convergence in volatilities).

Table V shows the average, intra-period volatility (as measured by standard deviation) for all periods and the last five periods of each session. It also shows treatment averages. During the last five periods in the six baseline sessions, the average standard deviation of Blue prices within a period was 19.76 francs. It was 12.23 francs for Green prices. In the sessions with short sales (OPIS), the average volatilities were 19.52 and 19.70 francs, respectively. In contrast, with direct portfolio trading (OPIP), the average volatilities were 27.87 and 26.74 francs, and, with an arbitrager, they were 27.65 and 27.40 francs. Both portfolio trading and active arbitrage trading increased volatility significantly. Comparing volumes in these sessions with others using a two-sample Wilcoxon tests and each session as an observation gives a statistic of 2.357 and p-value of 0.0184.

**Result 2.4: An Active Arbitrager Reduces Risk Sharing Efficiency**

Another concern of regulators is the degree of speculation and risk in financial markets. In the markets here, subjects were endowed with risky portfolios. However, because the aggregate endowment was fixed, they could all trade to zero-risk positions (by holding equal numbers of each claim). Define the market's risk sharing efficiency as the final percent of the certificates distributed in portfolios with

[16] For examples, see the debate over the New York Stock Exchange Rule 80A discussed in Overdahl and McMillan (1998).

matching complementary certificates.[17] Figuring efficiency in this manner, the endowed distributions represented 50% risk sharing efficiency.[18] Efficiency reaches 100% when all 80 certificates are held in risk free portfolios. Efficiency reaches 0% if every subject holds only one certificate type. Thus, efficiencies above 50% represent movements in the direction of risk sharing. It takes a minimum of 20 trades to achieve an efficient risk sharing distribution. Figure 1 shows this volume level for comparison.

The markets facilitated risk sharing on average. Average risk sharing efficiencies were highest for sessions with short sales, followed by baseline sessions, sessions with direct portfolio trading and with an arbitrager. Period efficiencies ranged from 27.5% (session OPIA-1, period 8) to 87.5% (session OPI-5(e), period 10). Average efficiencies ranged from 51.3% (session OPIA-1) to 68.7% (session OPIP-2). The overall average was 63.0%. Average risk sharing efficiencies were highest under the OPIS treatment (averaging 65.9%), and fell (in order) under OPI (65.4%), OPIP (59.7%) and OPIA (58.3%) treatments. Assigning a variable a value of 1 for the OPIS sessions, 2 for the OPI sessions, 3 for the OPIP sessions and 4 for the OPIA sessions and regressing it on efficiency gives a negative coefficient with a t-statistic of -2.286 (p-value=0.040). However, the differences between treatments were small. Risk sharing efficiencies were also negatively correlated with volumes in the markets. Overall, the correlation between the risk sharing efficiency in each period and volume in each period was -0.2595 (p-value = 0.001). The arbitrager facilitated much higher volumes and, through them, decreased risk sharing efficiencies.

To analyze the risk sharing at an individual level, define three self-determined trader types: diversifiers, who finish the period with an absolute difference in certificate number of less than 4 (the difference in the endowment); risk-takers, who finish the period with an absolute difference of more than 4; and others who finish with a difference of 4. Table VI shows the average trading profits (defined as the

[17] Originally, there are 80 certificates in each market all of which can be held in risk free portfolios. Efficiency is calculated by subtracting from 80 the absolute difference in the numbers of certificates of each type held by each subject and dividing by 80. (That is, subtracting from 100% the percentage of "exposed" certificates held in portfolios without certificates of the other type present to offset risk.)

[18] In each endowment, four certificates (two Blue and two Green) are consistent with risk averse subjects because holding these two "unit portfolios" exposes the subject to no risk. The four remaining certificates are consistent with risk seeking subjects because holding them exposes the subject to unnecessary risk. In arbitrage and short sale treatments efficiencies could be negative, though they never were.

difference between the expected value of the endowment and expected value of the final portfolio) for traders who diversified, traders who took on more risk and others. Generally, trading profits for diversifiers and other traders were insignificantly different from zero while risk takers' profits sometimes were significantly negative. Under all treatments except for direct portfolio trading, diversifiers outperformed risk takers significantly in expected profits and, simultaneously, decreased risk.

C. An Implication

**Implication: A Profit Maximizing, Monopolistic Arbitrager Would Not Eliminate Completely Behavioral Mis-Pricing Effects on Absolute Prices**

As the arbitrager in the three OPIA sessions, the experimenter exploited profitable arbitrage opportunities 439 times, missing 3 profitable opportunities. Arbitrage profits ranged from 1 to 250 francs per opportunity. Through arbitrage, the experimenter created a total of 878 new certificates, an average of 19.5 per period. (Recall, each market started with 80 certificates total. Thus, arbitrage activities increased the number of certificates available in the market by 24.39% on average. Creating certificates here is equivalent to short selling.) As discussed above, there was dramatic increase in volume in OPIA markets. Overall, acting as the arbitrager, the experimenter participated in 60% of the trades in the OPIA sessions. However, all of this activity was of little profit to the arbitrager. In total, the experimenter received 5,081 francs in profits ($2.54 total or about 0.6 cents per opportunity). This is because the experimenter exploited each and every arbitrage opportunity no matter how small. It is surprising that the profitability remained above 1 franc. Clearly, a profit-maximizing monopoly arbitrager would neither exploit all of the opportunities nor exploit none of them. Both rules lead to near zero profits. Even competitive arbitragers would require some profits. This is an experimental example of the limits of arbitrage as discussed by Shleifer and Vishny (1997). Optimally, arbitragers would only exploit some fraction of the opportunities and only drive prices part way to the no arbitrage bounds.

D. The Cause of the Bias

The behavioral mis-pricing in these markets is very robust. It is replicated in four designs and three sessions with minor changes here. The 15 sessions here give 223 replications of these single period markets with 140 different traders (10 traders participated in a second session). Further, the results are replicated by Forsythe, Rietz and Ross (1999) and by Weber, Keppe and Myer-Delius (2000) in slightly different contexts. Finally, Oliven and Rietz (2004) document arbitrage violations similar to those observed in the OPIA sessions in the long-running Iowa Electronic Markets populated by self-selected and, often, very experienced traders.

Several of the treatments here rule out specific explanations. OPIS sessions rule out short sale restrictions as a cause. OPI-4(m) explains specifically how to exploit opportunities and gives an example. Nevertheless, opportunities do not subside. OPI-5(e) uses experienced traders with little effect. OPI−6(r) removes anticipation of the outcome as an explanation by not revealing outcomes. While prices fall sometimes in the OPIP sessions, only in the OPIA treatments, with an arbitrager exploiting all opportunities, are prices consistently near no arbitrage bounds. However, this requires a great deal of effort on the part of the arbitrager and affects the markets adversely in other ways.

Forsythe, Rietz and Ross (1999) argue that "wishful thinking" influences prices. They show that giving subjects a vested interest in one outcome causes them to bid up prices in that outcome. If subjects have a natural preference for one state or another here (e.g., because of their endowed portfolio), they could bid up prices for preferred states beyond the state probability predictions in a similar manner. Weber, Keppe and Myer-Delius (2000) argue for a combined endowment and framing effect and present evidence consistent with it. They have subjects trade negative payoff gambles and reverse the direction of the pricing bias. This is consistent with a change in risk attitudes at a payoff of zero.

There is also direct evidence of an endowment effect here. Most subjects diversify away some of the risk. While they could always diversify away all risk, the amount of diversification seems to depend on the endowment for many subjects. Table VII shows the frequency with which $\chi^2$-tests of independence between endowments and final risk holdings give significant results. At the 90% level of confidence, we would expect 1 significant test per session if endowments and risk holding were truly independent. At the 95% level, we would expect 0.5 significant statistics per session. Actual rejection frequencies run 5 to 7 times the expected levels. The high frequency of dependence indicates that, for a substantial number of subjects, the risk held at the end of trading depended on the initial endowment. Thus, endowment effects appear to exist in these markets.

Such effects, along with Kahneman, Knetsch and Thaler's (1990) observation that the lack of willingness to sell is the dominant factor creating endowment effects, might explain why prices rise. In addition, an overall lack of willingness to sell the portfolio could explain why subjects may not exploit arbitrage opportunities. Thus, the overall evidence suggests a purchasing bias tied to an endowment effect is responsible for the degree of overpricing.

To test whether a purchasing bias is responsible, I ran one additional session under a treatment labeled OPIB. In this session, trading occurred in a manner similar to the main experiment. However, subjects were endowed with Blue and Green "currencies" of uncertain value and certificates with certain value. Each subject had eight certificates and a net endowment of 1,200 units of one currency and 2,400 units of the other. They traded currencies for certificates in two markets, one in Blue currency and one in Green currency. At the end of a trading period, subjects received a fixed amount for each certificate owned (200 points, which were converted into dollars at a known rate at the end of the session.) Also, at the end of the period, a subject drew a random marble from a bucket containing six blue marbles and twelve green marbles. If a blue marble was drawn, subjects received one point for each unit of Blue currency held (after fixed costs were subtracted) and zero points for each unit of Green currency held. If a green marble was drawn, subjects received points for Green currency instead of Blue. Because subjects were endowed with large amounts of currency, and assessed fixed costs at the end of trading, they could effectively short up to 30,000 units of each currency. This design reversed the interpretations of the units of account and the traded items. In the main experiment, subjects traded certain value currencies (as the unit of account) for risky traded certificates (the contingent claims). In this session, subjects traded risky currencies (using the contingent claims as the unit of account) for certain value certificates. Allocation, pricing and arbitrage predictions for this session are analogous to the main design. However, prices that are "too high" here indicate contingent claim valuations that fall below predictions.

As in the main experiment, price predictions in this session come from equating expected values of the contingent claims and the certain asset. In this case, the expected value of a unit of Blue currency is 1/3. Equating this to the certain value of 200 gives a certificate price prediction of 600 units of Blue currency. Similarly, the price in terms of Green currency is 300. The inverses of these prices give the predicted values of the contingent claims: 1/600 and 1/300 certificates, respectively.

In actual trading, subjects' confusion over trading in two currencies with uncertain values resulted in high price variances relative to the main design. Nevertheless, on average, certificates were overpriced (contingent claims were undervalued). Summed average (within a period) prices averaged (across periods) 991 across all periods of the session and 1,017 across the last five periods. This represents 10% and 13% overpricing relative to the expected summed value of 900. This compares to 14.5% to over 20% for the non-arbitrage sessions in the main experiment. As in the main experiment, arbitrage violations in this treatment were all consistent with overbidding. What differs is the market characterization of currency and commodities. In the main experiment, the contingent claims were the commodities traded in the market in exchange for currency with a certain value. In this session, the commodities traded were of certain value and the currencies exchanged for them were the contingent claims. So, in this case, the subjects undervalued their endowment of contingent claims. The bias still seems related to endowments and an unwillingness to sell endowed goods in a market. But, this session brings out the importance of the structure and terminology of the market in framing the endowment effect as a purchasing bias.

## IV. Discussion and Conclusions

These experimental asset markets give two primary results that contribute to the debate over behavioral finance. (1) As suggested by behavioral finance, pervasive behavioral anomalies (here, an endowment-based purchasing bias) can affect aggregate outcomes in financial markets (here, resulting in higher than rational prices that violate no arbitrage restrictions). The resulting behavioral mis-pricing is extremely robust. (2) As suggested in counter arguments to behavioral finance, a sufficiently active arbitrager can drive prices toward no arbitrage bounds. However, it involves a great deal of arbitrage activity for little profit. I conclude that, while a profit maximizing arbitrager may mitigate the effects of the purchasing bias on absolute mis-pricing, he or she will not drive it completely out of existence. At the least, they will need to cover costs. Thus, there are limits to the argument that arbitragers will exploit mis-pricing caused by behavioral factors and drive them out of existence.

Beyond the evidence it provides on behavioral finance, this research documents how arbitragers affect markets in general by comparing otherwise identical markets with and without active arbitragers. This research shows that we cannot automatically expect arbitrage-free pricing. While bringing absolute prices in line with no-arbitrage bounds, an active arbitrager increases volume dramatically, increases volatility, increases short positions (by creating certificates in these markets), drives risk sharing efficiency down slightly and, if anything, drives relative prices out of line. The research also shows the limits of arbitrage (Shleifer and Vishny, 1997) in a controlled context: Profit maximizing arbitragers will not bring prices completely into line. Doing so would result in near zero profits. Arbitragers can only profit if they allow some deviation from no-arbitrage limits before exploiting arbitrage opportunities. Hence, small arbitrage profits often observed in the literature are not surprising.

The results are important for researchers in the burgeoning area of prediction markets.[19] The markets run here are essentially small-scale, controlled versions of prediction markets like the Iowa Electronic Markets. Without an arbitrager, relative prices are more efficient than absolute prices and the

[19] See Berg, Forsythe, Nelson and Rietz, 2003, for references to the increasingly popular use of prediction markets.

common practice of "normalizing" prices (dividing individual prices by their sum) results in both (1) prices that can be interpreted as probabilities (because they sum to 1) and (2) prices that more closely reflect true underlying state probabilities. This is true even when absolute prices do not meet arbitrage criteria.[20] While normalization appears to have worked in practice, the research here provides clear documentation in a controlled environment where underlying state probabilities are known with certainty.

There are additional results of interest. For market microstructure research, the evidence here suggests no shortage of noise traders (those trading for sub-optimal reasons). However, one might want to model noise traders as driven by behavioral phenomena, not just making random trades. Left unchecked, the behavioral mis-pricing has welfare implications: it hurts traders who are more prone to the bias. One benefit of the arbitrager driving down prices is that it protects biased traders from their own mistakes. When prices are driven down to no-arbitrage levels, certificate buyers neither gain nor lose on average. The behavioral bias affects absolute prices, which would challenge models based on absolute prices or returns (e.g., CAPM). But, the biases to not affect relative prices as much, which would allow models based on relative prices or returns (e.g., APT) to retain some validity. Finally, reversing the market framing of commodities and units of exchange reverses the bias in valuation. When contingent claims are the traded commodity, their prices are too high. Subjects value claims above their expected values. When, the claims are used as the unit of exchange, market prices remain high. This implies that subjects value the claims below expected value. This implies a new market-structure-based framing effect that goes beyond typical frames of uncertainty versus certainty and gains versus losses.

Overall, these results imply a complex relationship between biases and outcomes in financial markets. The results here indicate that how biases affect markets will depend on (at least) the strength of the biases, how markets are structured and the interplay of arbitragers and biased traders. Clearly, there is a need for more research to understand biases and outcomes in both controlled and field environments.

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[20] The justification for routine normalization in most prediction market research is to control for asynchronous trading. See Berg, Forsythe, Nelson and Rietz, 2003.

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## Appendix I: The Economic Environment and Theoretical Predictions

The markets studied in this paper are for claims with payoffs that are uncorrelated with anything else affecting the wealth of the agents. Because of this, the experiments can be treated as isolated economies. Here, I introduce notation and develop the theoretical asset pricing relationships.

Consider an economy with many individuals (denoted by $i$=1,2,...,$N$, here representing the experimental subjects), a single type of "good" (the experimental currency) and random "states of nature" drawn from a finite set, Ω (the payoff determining ball draws, here "blue" or "green"). Let $\pi^{\omega}$ be the probability of state ω occurring. Define $x_i^{\omega}$ as individual $i$'s endowment of the good in state ω (this represents the subject's endowment of claims). The total endowment is then $\sum_{i=1}^{N} x_i^{\omega}$. Let $y_i^{\omega}$ represent individual $i$'s contingent consumption of the good in state ω (this represents the subject's post-trade holding of claims). Finally, let $P^{\omega}$ be the price of a contingent claim for one unit of the good in state ω.

If individuals are risk seeking, the Pareto optimal distribution is for all subjects to hold only one type of claim. Then, prices may deviate from expected values. Otherwise, prices should equal expected values, independent of the exact risk preferences of subjects. Suppose that individuals have risk neutral, von-Neumann-Morgenstern utility functions. Then, it is trivial to show that prices of the claims will expected values or, appropriately scaled, state probabilities. Next, I show that even if subjects are risk averse, equilibrium prices should equal expected values.

Suppose individuals have von Neumann-Morgenstern utility functions for consumption in each state that are increasing, concave and once-differentiable. Then, Caspi (1974) proves that if states ω' and ω'' have the same total endowments, the set of Pareto optimal allocations under ω' and ω'' will be identical. Competitive equilibrium should result in $y_i^{\omega'} = y_i^{\omega''}$ for all individuals *regardless of the initial endowments* in the two states. That is, individuals will hold an equal number of contingent claims for consumption across states characterized by the same total endowment. Further, Malinvaud (1974) shows that the price ratios for contingent claims for consumption across these states should equal the ratios of the state probabilities. These relative prices will hold *regardless of the level of risk aversion*.

In each experimental period, the total endowment is the same *in every state*. That is, the states only differ by the distribution of the endowments. In this case, the prices for claims on the endowment in each state must add up to the known aggregate endowment (which does not vary across states). Thus, after normalizing by the endowment, prices must sum to one. Put simply, no-arbitrage restrictions imply the properly normalized price for a contingent claim for the good in state ω is $\pi^{\omega}$.[21] In this case, both relative and absolute prices are independent of the level of risk aversion. Intuitively, expected value pricing comes from the fact that there is no aggregate risk in the market and, therefore, no aggregate risk premium.

Overall, traditional rational agent/efficient markets arguments imply four relationships in these experimental sessions:

[21] Of course, if individuals assign subjective probabilities to states that differ from the true probabilities, then normalized prices will equal these subjective probabilities.

a) Risk Allocation: Each individual will hold contingent claims giving rights to the same consumption level in all states, i.e.: $y_i^{\omega} = \bar{y}_i \; \forall \omega \in \Omega$.

b) Relative Value Pricing: The ratio of prices for contingent claims for consumption in states ω and ω' equals the ratio of the probabilities of state ω and ω' occurring, i.e.: $\frac{P^{\omega}}{P^{\omega'}} = \frac{\pi^{\omega}}{\pi^{\omega'}} \; \forall \omega, \omega' \in \Omega$. In this case, the price ratio of blue to green prices is 6/14 = 0.4286.

c) No Arbitrage Pricing: Contingent claim prices always sum to the fixed portfolio dividend, i.e.: $\sum_{\omega \in \Omega} P^{\omega} = C$, where *C* is the fixed dividend. In these sessions, *C*=1,000.

d) Absolute Pricing: The normalized price of a contingent claim for consumption in state ω is equal to the probability of state ω, i.e.: $P^{\omega} = \pi^{\omega} \times C$, where *C* is the fixed dividend. In these sessions, *C*=1,000, $P^{Blue} = 300$ and $P^{Green} = 700$.

The risk allocation result of complete diversification should hold for all individuals who have concave utility functions, regardless of their specific levels of risk aversion. Relative pricing should hold as long as some individuals trade in all contingent claims, regardless of risk preferences. No arbitrage pricing should hold as long as individuals value more of the good to less. Finally, absolute pricing follows directly from relative pricing and no arbitrage pricing. Absolute pricing should hold as long as individuals prefer more of the good to less and some can trade in all claims, regardless of risk preferences.

These results can be derived from typical asset pricing models in finance as well. CAPM and APT say that the returns to assets will depend on the risk free rate and the correlation of asset returns to aggregate risk factors. The return to cash holdings in the experiments is zero. In each experimental session, there is no aggregate risk and, therefore, no aggregate risk factor. The claim payoffs are uncorrelated with outside wealth. So, the return to each claim equals the risk free rate of zero plus a zero risk premium. Since the return is zero, the claims must be priced at expected values in equilibrium. Option pricing theory says that the claims will have zero expected return (be priced at expected value) relative to the risk neutral distribution. The risk neutral distribution differs from the true distribution due to hedging demands. However, since claim payoffs are uncorrelated with outside wealth, they cannot be used for hedging. As a result, risk neutral and true probability distributions will be the same and the claims will be priced at true expected values.

Appendix II: Instructions

This appendix gives the instructions sets used and sample record sheets. The text of instruction sets for specific treatments contained only the general text and passages marked for that specific treatment. It did not contain passages marked for other treatments. Each subject had a copy of the instructions. They were read aloud and all questions were answered before the sessions began.

GENERAL INSTRUCTIONS

This is an experiment in the economics of market decision making. The instructions are simple. If you follow them carefully and make good decisions, you might earn a considerable amount of money which will be paid to you in cash at the end of the experiment. With these instructions you will find sheets labeled “INFORMATION AND RECORD SHEET” and “PROFIT SHEET AND RECEIPT”. These will help you determine the value to you of any decisions you might make.

In this experiment we are going to conduct markets in which you will buy and sell two types of certificates in a sequence of market periods. In each period you will have both certificates and currency. You can use the currency to buy and sell certificates or you can save it.

The type of currency used in these markets is francs. All trading and earnings will be in terms of francs. At the end of the experiment, each franc will be worth $________ to you. Do not reveal this number to anyone. At the end of the experiment, your francs will be converted to dollars at this rate, and you will be paid in dollars. Notice that the more francs you earn, the more dollars you will earn.

SPECIFIC INSTRUCTIONS

Your profits during this experiment come from two sources: (1) from collecting dividends on certificates you hold at the end of each period and (2) from buying and selling certificates.

There will be two types of certificates in this experiment, “Blue” certificates and “Green” certificates. During each market period you are free to purchase or sell as many certificates of each type as you wish, provided you follow the rules below. Each period, there will be *separate* markets for Blue and Green certificates. `**Treatment OPIP:** In addition, there will be a market called “Both” in which you can buy and sell both certificates simultaneously.**]** During each period, you may buy and sell certificates in **[Treatments OPI, OPI(m), OPI(e), OPI(r), OPIS & OPIA:** both**]** **[Treatment OPIP:** all three**]** markets. **[Treatment OPIS:** In addition, after trading ceases in these markets, there will be a market called “Both” in which you can buy both certificates simultaneously from the experimenter for a fixed price. We will discuss the reasons for the “Both” market and how it works in more detail later.**]**

For each certificate of each type you hold at the end of the period you will receive a dividend. The size of the dividend you will receive on each certificate will depend both on the certificate type and on the outcome of a random event. Specifically, we have a bucket which contains twenty (20) colored marbles of identical size. Six (6) of these marbles are blue and fourteen (14) are green. Each period, one of you will draw a marble from the bucket without looking. The dividend for each certificate type will be determined by the marble drawn according to the following DIVIDEND TABLE:

**[Treatments OPI, OPI(e), OPI(r), OPIP, OPIS and OPIA:**

| DIVIDEND TABLE | | |
|---|---|---|
| Certificate Type | Color of Marble Drawn | |
| | BLUE (There are 6 blue marbles.) | GREEN (There are 14 green marbles.) |
| BLUE | 1000 Francs | 0 Francs |
| GREEN | 0 Francs | 1000 Francs |

**]**

**[Treatment OPI(m):**

| DIVIDEND TABLE | | |
|---|---|---|
| Certificate Type | Color of Marble Drawn | |
| | BLUE (There are 6 blue marbles.) | GREEN (There are 14 green marbles.) |
| BLUE | 1000 Francs | 0 Francs |
| GREEN | 0 Francs | 1000 Francs |
| Unit Portfolio (1 Blue and 1 Green) | 1000 Francs | 1000 Francs |

**]**

After the level of the dividend for each certificate type has been determined, the marble drawn will be returned to the bucket so they will all be there for the next draw.

Total certificate earnings are calculated by multiplying the dividend for each type of certificate by the number of certificates held of each type and adding the results. That is:

Total Certificate Earnings = (Dividend for Blue Certificates) H (Number of Blue Certificates Held)
+ (Dividend for Green Certificates) H (Number of Green Certificates Held).

Suppose, for example, that you hold five Blue certificates and two Green certificates at the end of a period. If a blue marble is drawn at the end of that period, you would receive dividends of 1000 francs for each Blue certificate and 0 francs for each Green Certificate. Your total certificate earnings in that period would be 1000H5 + 0H2 = 5000 francs. If a green marble is drawn at the end of that period, you would receive dividends of 0 francs for each Blue certificate and 1000 francs for each Green Certificate. Your total certificate earnings in that period would be 0H5 + 1000H2 = 2000 francs.

**[Treatment OPI(m):** Notice that, for each "unit portfolio" you hold consisting of one of each certificate type, you receive 1000 francs when either a blue or green marble is drawn. Thus, you always receive at least 2000 francs in the above example because you hold two unit portfolios. That is, holding five Blue certificates and two green certificates implies you hold two unit portfolios and three additional Blue certificates.**]**

**[Treatment OPI(r):** Notice that, for each "unit portfolio" you hold consisting of one of each certificate type, you receive 1000 francs when either a blue or green marble is drawn. Thus, you always receive at least 2000 francs in the above example because you hold two "unit portfolios". That is, holding five Blue certificates and two green certificates implies you hold two unit portfolios, which will give you 2000 francs with certainty, and three additional Blue certificates, which will give you an additional 3000 francs only if a blue marble is drawn.

After each period, you will calculate your earnings for each type of marble that could be drawn. However, you will not be told which marble was actually drawn after each period. Instead, while the subject who drew the marble watches to insure accuracy, the experimenter will enter the marble color into a computer which will keep track of your actual profits period by period. At the end of the experiment, the computer will total your profits and you will be paid in cash.**]**

Note, the DIVIDEND TABLES are the same for each participant. Thus, the dividend on each certificate does not depend on who owns it at the end of the period.

## INVENTORIES OF CERTIFICATES AND CASH ON HAND

At the beginning of each period, you are provided with initial inventories of each type of certificate. These inventories are recorded in Row 0 of each period's INFORMATION AND RECORD SHEET. You may sell these if you wish, or you may hold them. You may also purchase certificates and increase your inventories. For each of the certificates of each type that you hold at the end of the period, you will receive the dividend corresponding to the certificate type and the marble drawn at the end of the period.

The amount of francs that you have at any particular time will be called "cash on hand". At the beginning of each period you are provided with an initial amount of cash on hand. This amount is given on your INFORMATION AND RECORD SHEET. Sales from your certificate inventories increase your cash on hand by the amount of the sale price. Similarly, purchases reduce your cash on hand by the amount of the purchase price. Thus you can gain or lose money on the purchase and resale of certificates. **[Treatments OPI, OPI(m), OPI(e), OPIS, OPIP & OPIA:** At the end of the period, you will be paid the earnings on your certificate inventories. This will be added to your cash on hand. Then you will figure your profits for the period and a new period will begin.**]** **[Treatment OPI(r):** At the end of the period, you will determine the earnings on your certificate inventories for each possible marble draw. Your actual earnings will be added to your cash on hand to determine your profits for the period.**]**

Thus, at the beginning of each period you will be endowed with initial inventories of certificates and with an initial amount of cash on hand. Do not reveal these amounts to anyone. They are for your own private information. You are free to buy and sell certificates as you wish according to the rules below. Your total francs at the end of the period are determined by your initial amount of cash on hand, earnings on certificate inventories at the end of the period and by gains and losses from purchases and sales of certificates. All of the cash on hand at the end of each period in excess of the "fixed cost" of ________ francs are yours to keep.

MARKET ORGANIZATION

The markets for certificates are organized as follows. The markets will be conducted in a series of periods. Each period will last for ___ minutes. Anyone wishing to buy a certificate is free to raise his or her hand and make a verbal bid in that certificate's market to buy one certificate at a specified price. Anyone **[Treatments OPI, OPI(m), OPI(e), OPI(r), OPIP & OPIA:** with certificates of that type to sell**]** **[Treatment OPIS:** is free to accept or not accept the bid.**]** Likewise, anyone wishing to sell a certificate is free to raise his or her hand and submit a verbal offer in that certificate's market to sell one certificate at a specified price. Anyone with enough cash on hand to buy that certificate is free to accept or not accept the offer.

**[Treatment OPIP:** In addition, anyone wishing to buy one of each type of certificates simultaneously is free to raise his or her hand and make a verbal bid in the "Both" market to buy both certificates at a specified price. Anyone with one of each type of certificates to sell is free to accept or not accept the bid. Likewise, anyone wishing to sell a certificate of each type simultaneously is free to raise his or her hand and submit a verbal offer in the "Both" market to sell both certificates at a specified price. Anyone with enough cash on hand to buy both certificates is free to accept or not accept the offer.**]**

**[Treatment OPIA:** The experimenters will participate directly in the markets in the following manner and only in the following manner. If there are bids outstanding for both certificates and these bids sum to more than 1,000 francs, the experimenters will accept both bids. That is, if the experimenters can sell one of each certificate type simultaneously for a total that exceeds 1,000 francs, they will do so. (The experimenters' trader ID number will be zero.) Similarly, if there are two offers outstanding and these offers sum to less than 1,000 francs, the experimenters will accept both offers. That is, if the experimenters can buy one of each certificate type simultaneously for a total of less than 1,000 francs, they will do so. These are the only times that the experimenters will participate directly in the market.**]**

If a bid or offer is accepted, a binding contract has is made for a single certificate **[Treatment OPIP:** (in the Blue or Green markets) or a "unit portfolio" of one of each certificate type (in the "Both" market)**]**. At that time, the contracting parties must record the transaction on their INFORMATION AND RECORD SHEETS and determine their new levels of cash on hand and certificate inventories. **[Treatment OPIS:** You are allowed to let your inventories of certificates fall below zero during trading.**]** Any ties in bids, offers or their acceptance will be resolved by random choice. After a contract has been made, you are free to submit any new bids or offers that you wish.

There are likely to be many bids and offers that are not accepted, but you are free to keep trying. You are free to make as much profit as you can.

**[Treatment OPIS:** If you have a negative inventory of either certificate type at the end of market trading in a period, you will have to purchases certificates from the experimenter. You must purchase the same number of certificates of each type from the experimenter. You will be charged 1,000 francs for each "unit portfolio" of one Blue and one Green certificate you purchase. You must purchase enough unit portfolios to increase your inventories of both types of certificate to at least zero. For example, if, when trading ceases, you have -2 Blue certificates and 3 Green certificates, you must purchase 2 unit portfolios from the experimenter. This will cost you 2,000 francs and add 2 certificates to both of your inventories. Then, your end of period inventories will be 0 Blue certificates and 5 Green certificates. You will be paid dividends on these end of period inventories.**]**

**[Treatments OPI, OPI(m), OPI(e), OPIP, OPIS & OPIA:** At the end of each period, one of you will draw a marble and determine the dividend for each certificate type for that period. You will use these dividends to calculate your total certificate earnings and your profits for the period. After all participants have calculated their profits, the next period will start. For the next period, use the INFORMATION AND RECORD SHEET with the appropriate period number in your packet.**]**

**[Treatment OPI(r):** At the end of each period, the subject who draws marbles will draw a marble and determine the dividend for each certificate type for that period. The computer will use these dividends to calculate your total certificate earnings and your profits for the period. After the marble color has been entered in the computer, the next period will start. For the next period, use the INFORMATION AND RECORD SHEET with the appropriate period number in your packet.**]**

Except for making bids, offers or acceptances and asking the experimenter questions, you are not to speak to anyone until this experiment is over. If you break silence, you will be given one warning. If you break silence again, you will lose any earnings you have and be asked to leave the experiment.

TRADING AND RECORDING RULES[22]

**[Treatments OPI, OPI(m), OPI(e), OPI(r) and OPIA:** 1. All transactions are for one certificate at a time.**]**

**[Treatment OPIP:** I.A.1. All transactions in the "Blue" or "Green" markets are for one certificate at a time. All transactions in the "Both" market are for one "unit portfolio" consisting of each certificate type at a time.**]**

**[Treatment OPIS:** I.A.1. All transactions in the "Blue" or "Green" markets are for one certificate at a time. All purchases in the "Both" market are for equal numbers of each certificate type at a price of 1,000 for each "unit portfolio" of two certificates.**]**

2. BIDS (TO BUY) ARE SUBMITTED stating your ID number, that you are making a bid, the amount of the bid and the market in which you are bidding.

   For example, trader 4 would submit a bid to buy a Green certificate for 500 by stating: "4 Bids 500 for Green."

3. BIDS ARE ACCEPTED (SELLING A CERTIFICATE) by stating you ID number, that you are accepting a bid and the market(s) in which you are accepting the bid.

   For example, trader 7 would sell a Green certificate at the outstanding bid of 500 by stating: "7 accepts the Green bid." **[Treatment OPIP:** Trader 7 would accept the bid in the "Both" market by stating, "7 accepts the 'Both' bid."**]** Trader 7 could accept both the Green and Blue bids by stating: "7 accepts the Blue and Green bids."

4. Bids must be higher than the last outstanding bid unless a contract has just been made.

5. OFFERS (TO SELL) ARE SUBMITTED by stating your ID number, that you are making an offer, the amount of the offer and stating the market in which you are offering.

   For example, trader 6 would submit an offer to sell a Blue certificate for 500 by stating: "6 Offers Blue at 500.

[22] These rules appeared on one sheet in each set of instructions so that subjects could refer to them all at one time.

6. OFFERS ARE ACCEPTED (BUYING A CERTIFICATE) by stating your ID number, that you are accepting an offer and the market(s) in which you are accepting the offer.

For example, trader 2 would buy a Blue certificate at the outstanding offer of 500 by stating: "2 accepts the Blue offer." **[Treatment OPIP:** Trader 2 could accept the offer in the "Both" market by stating: "2 accepts the 'Both' offer."**]** Trader 2 could accept both the Blue and Green offers by stating: "2 accepts the Blue and Green offers."

7. Offers must be lower than the last outstanding offer unless a contract has just been made.

8. After each of your sales or purchases you must record the TRANSACTION PRICE in the appropriate column of your information and record sheet depending on the nature of the transaction. The first transaction is recorded on Row 1 and succeeding transactions are recorded on subsequent rows.

9. After each transaction you must calculate and record your new inventories of certificates and your new cash on hand. **[Treatments OPI, OPI(m), OPI(e), OPI(r), OPIP & OPIA:** Your inventories of certificates may NEVER GO BELOW ZERO.**]** **[Treatment OPIS:** Your inventories of certificates MAY go below zero during the trading period. However,**]** Your francs on hand may NEVER GO BELOW ZERO.

**[Treatments OPI, OPI(m), OPI(e), OPIP, OPIS and OPIA:** 10. At the end of the period you must:
**[Treatment OPIS only:** i. Purchase enough unit portfolios from the experimenter so that both of your certificate inventories are at least zero.**]**

ii. Record your final inventories and cash on hand on row 25.
iii. Record the dividends and your total certificate earnings in rows 26 and 27.
iv. Find your total end of period cash on hand by adding your certificate earnings to your cash on hand. Place the result in row 28.
v. Subtract from your cash on hand the amount listed in row 29 and enter this new amount on row 30. This is your profit for the market period and is yours to keep.
vi. Finally, record your end of period net profits on your PROFIT SHEET.

11. At the end of the experiment add up your total profit on your PROFIT SHEET. To convert this number into dollars, multiply it by your conversion rate. Place the result in the receipt section and the experimenter will pay you this amount of dollars in cash.**]**

**[Treatment OPI(r):** 10. At the end of the period:

i. Record your final inventories and cash on hand on row 24 and record your cash on hand in both blank columns of row 26.
ii. Record the dividends from each possible marble draw on row 27.
iii. Find the two possible values of your end of period cash on hand by adding your certificate earnings to your cash on hand. Place the results in row 28.
iv. Finally, determine your two possible levels of end of period net profits by subtracting the amounts listed in row 29. Enter these new amounts on row 30. The number in the "Blue Marble" column will be your profit for the market period if a blue marble is drawn at the end of this period. The number in the "Green Marble" column will be your profit for the market period if a green marble is drawn at the end of this period. One of these numbers will be added to your profits for the experiment according to the marble drawn.

11. At the end of the experiment, the computer will total your profits from each period of the experiment. You will be given this number. To convert this number into dollars, multiply it by your conversion rate. Place the result in the receipt section and the experimenter will pay you this amount of dollars in cash.**]**

**[Additional Instructions Distributed and Explained after Period 8 in OPI-4(m):**

ADDITIONAL INSTRUCTIONS

Because a unit portfolio will always pay you 1000 francs in dividends, you will always profit if you sell one Blue and one Green certificate at prices that total more than 1000 francs. Similarly, you will always profit if you buy one Blue and one Green certificate at prices that total less than 1000 francs.**]**

INFORMATION AND RECORD SHEET

Participant # ___ Period # 1

| Row | TRANSACTION INFORMATION | | | INVENTORIES | | Cash on Hand |
|---|---|---|---|---|---|---|
| | Cert. Type B and/or G | Sale Price (8 Cash, 9 Inv) | Purc. Price (9 Cash, 8 Inv) | Blue Certificates | Green Certificates | |
| 0 | INITIAL VALUES: | | | | | |
| 1 | | | | | | |
| 2 | | | | | | |
| . . . | . . . | . . . | . . . | . . . | . . . | . . . |
| 24 | | | | | | |
| 25 | FINAL VALUES: | | | | | |
| 26 | Blue Cert. Earnings _____ H Final Blue Cert. Inventory _____ = | | | | | |
| 27 | Green Cert. Earnings _____ H Final Green Cert. Inventory _____ = | | | | | |
| 28 | Total Cash on Hand + Certificate Earnings = | | | | | |
| 29 | (-) Fixed Costs = | | | | | |
| 30 | End of Period Net Profits = | | | | | |

Tables

Table I: Experimental design parameters

| General parameters | |
|---|---|
| Subjects: | University of Iowa MBA's and Undergraduates.<br>All sessions except OPI-5(e) used subjects without previous experience in other markets run for this paper.<br>Session OPI-5(e) used subjects with experience in one previous session run for this paper. Subjects commonly knew this experience level.<br>10 Subjects per Session. |
| Time and Payments: | Subjects were recruited for 3 hours.<br>Experiments lasted for approximately 2.5 hours.*<br>Earnings averaged \$30.00 and ranged from \$17.70 to \$40.50.<br>Francs were exchanged at the rate of \$0.0005 per franc. |
| Endowments and Fixed Costs: | Subjects began each period with 40,000 francs and either<br>1) 2 Blue Certificates and 6 Green Certificates or<br>2) 6 Blue Certificates and 2 Green Certificates.<br>A Fixed cost of 40,000 francs was subtracted after each period.<br>In OPI-6(r), state feedback was given only at the end of the experiment. |
| Number And Time of Periods: | There were 15 periods in each experiment.<br>Subjects began each experiment with record sheets for 15 periods.<br>Each period lasted 5-7 minutes (with period times announced in advance). |
| Dividend Structure: | Dividends each period were determined by a marble drawn randomly from a bucket containing 20 marbles according to the following table: |

| Color | Number | Blue Certificate Dividend | Green Certificate Dividend |
|---|---|---|---|
| Blue | 6 | 1,000 Francs | 0 Francs |
| Green | 14 | 0 Francs | 1,000 Francs |

| Treatment Variables | |
|---|---|
| OPI Treatment: | No Short Sales<br>Expanded Payoff Table and Instructions in OPI-4(m)<br>Experienced Subjects Participated in OPI-5(e)<br>Subjects received no feedback on states in OPI-6(r) |
| OPIS Treatment: | Short Sales Allowed |
| OPIP Treatment: | Direct Portfolio Trading Allowed |
| OPIA Treatment: | Experimenter Enforced Arbitrage Restrictions |

*Experiment OPIA-2 ran for just over 3 hours with all the subjects' consent.

Table II: Summary of arbitrage opportunities between the Certificates and the final portfolio value

| Session: | No. of events* | No. of non-trade events** (% of events) | Both Blue and Green bids outstanding (% of non-trade events) | Blue plus Green bids exceed 1,000 (% of both outstanding) [Average profit available] | Both Blue and Green offers outstanding (% of non-trade events) | Blue plus Green offers less than 1,000 (% of both outstanding)[average profit available] |
|---|---|---|---|---|---|---|
| OPI-1 | 1005 | 726 (72.24) | 149 (20.52) | 149 (100) [184.46] | 285 (39.26) | 0 (0) [0] |
| OPI-2 | 778 | 561 (72.11) | 36 (6.42) | 16 (44.44) [128.13] | 188 (33.51) | 0 (0) [0] |
| OPI-3 | 1048 | 754 (71.95) | 177 (23.47) | 174 (98.31) [279.31] | 177 (23.47) | 0 (0) [0] |
| OPI-4(m) | 1155 | 815 (70.56) | 221 (27.12) | 172 (77.83) [160.76] | 94 (11.53) | 0 (0) [0] |
| OPI-5(e) | 724 | 500 (69.06) | 129 (25.80) | 123 (95.35) [127.28] | 108 (21.6) | 0 (0) [0] |
| OPI-6(r) | 935 | 699 (74.76) | 194 (27.75) | 190 (97.94) [157.61] | 322 (34.44) | 0 (0) [0] |
| OPIP-1 | 1193 | 883 (74.02) | 152 (17.21) | 132 (86.84) [190.04] | 154 (17.44) | 0 (0) [0] |
| OPIP-2 | 989 | 740 (74.82) | 332 (44.86) | 188 (56.63) [117.97] | 22 (3.97) | 1 (4.55) [15] |
| OPIP-3 | 1013 | 701 (69.20) | 214 (30.53%) | 34 (15.89) [33.09] | 118 (16.83) | 2 (1.69%) [125] |
| OPIS-1 | 404 | 265 (65.59) | 33 (12.45) | 31 (93.94) [177.42] | 28 (10.57) | 0 (0) [0] |
| OPIS-2 | 729 | 535 (73.39) | 181 (33.83) | 133 (73.48) [180.90] | 58 (10.84) | 0 (0) [0] |
| OPIS-3 | 531 | 328 (61.77) | 79 (24.09) | 66 (83.54) [97.72] | 55 (16.77) | 0 (0) [0] |
| OPIA-1 | 1283 | 976 (76.07) | 243 (24.90) | 114 (46.91) [12] | 43 (4.41) | 0 (0) [0] |
| OPIA-2 | 1121 | 753 (67.17) | 162 (21.51) | 98 (60.49) [32.48] | 108 (14.34) | 0 (0) [0] |
| OPIA-3 | 1077 | 719 (66.76) | 252 (35.05) | 230 (91.27) [3.39] | 6 (0.83) | 0 (0) [0] |

Table III: Summary of arbitrage opportunities between the certificates and the traded portfolio price

| Session: | No. of events* | No. of non-trade events** (% of events) | Both Blue and Green bids outstanding with portfolio ask outstanding (% of non-trade events) | Blue plus Green bids exceed portfolio ask (% of all outstanding) [Average profit available] | Both Blue and Green asks outstanding with portfolio bid (% of non-trade events) | Blue plus Green asks less than portfolio bid (% of both outstanding) [Average profit available] |
|---|---|---|---|---|---|---|
| OPIP-1 | 1193 | 883 (74.02) | 95 (10.76) | 8 (8.42) [59.38] | 35 (3.96) | 0 (0.00) [0.00] |
| OPIP-2 | 989 | 740 (74.82) | 0 (0.00) | 0 (0.00) [0.00] | 3 (0.41) | 0 (0.00) [0.00] |
| OPIP-3 | 1013 | 701 (69.20) | 91 (12.98) | 0 (0.00) [0.00] | 18 (2.57) | 0 (0.00) [0.00] |

Table IV: Overall Trading Tendencies and Profits

| Treatment | Buyers' Trading Profit* Average (Std. Dev.) *obs.* | Others' Trading Profit* Average (Std. Dev.) *obs.* | Sellers' Trading Profit* Average (Std. Dev.) *obs.* | t-test for Difference in Means between Buyers' and Sellers' Trading Profits* Difference *t-statistic* (Prob>\|t\|) |
|---|---|---|---|---|
| Baseline | -344.25** (379.57) *249* | 16.75 (312.65) *431* | 392.50** (427.57) *200* | 736.75 *19.3182*** (0.0000) |
| Direct Portfolio Trading | -180.04** (376.64) *117* | -8.12 (396.38) *221* | 204.11** (347.87) *112* | 384.15 *8.0085*** (0.0000) |
| Short Sale | 227.22** (229.73) *124* | 24.88 (276.56) *216* | 204.09** (225.20) *110* | 431.31 *14.4674*** (0.0000) |
| Arbitrager | -93.51** (452.85) *207* | 39.59 (604.84) *194* | 189.24** (325.92) *49* | 282.76 *4.1225*** (0.0001) |

*Trading profits are the difference in expected value between the final portfolio and the initial portfolio of the trader including cash on hand and certificates

**Significantly different from zero at the 95% level of confidence.

Table V: Average intra-period price volatility (measured by standard deviation)

| Session | Overall volatility | | | Volatility in the last 5 periods | | |
|---|---|---|---|---|---|---|
| | Blue | Green | Summed | Blue | Green | Summed |
| OPI-1 | 20.29 | 22.52 | 42.81 | 6.77 | 3.87 | 10.65 |
| OPI-2 | 31.29 | 28.64 | 59.93 | 19.60 | 11.61 | 31.21 |
| OPI-3 | 36.09 | 36.32 | 72.41 | 31.31 | 18.48 | 49.79 |
| OPI-4(m) | 42.02 | 43.51 | 85.54 | 6.77 | 3.87 | 10.65 |
| OPI-5(e) | 13.49 | 13.33 | 26.82 | 25.37 | 19.29 | 44.66 |
| OPI-6(r) | 87.85 | 40.09 | 127.94 | 28.70 | 16.26 | 44.97 |
| All OPI Sessions | 38.51 | 30.74 | 69.24 | 19.76 | 12.23 | 31.99 |
| OPIP-1 | 60.48 | 39.15 | 99.63 | 40.45 | 27.37 | 67.82 |
| OPIP-2 | 27.14 | 35.03 | 62.17 | 26.80 | 28.43 | 55.23 |
| OPIP-3 | 31.32 | 48.00 | 79.32 | 16.35 | 24.42 | 40.77 |
| All OPIP Sessions | 39.65 | 40.73 | 80.37 | 27.87 | 26.74 | 54.61 |
| OPIS-1 | 30.66 | 36.75 | 67.41 | 19.56 | 11.79 | 31.35 |
| OPIS-2 | 45.22 | 73.78 | 119.00 | 27.53 | 29.93 | 57.46 |
| OPIS-3 | 24.17 | 25.21 | 49.37 | 11.46 | 17.40 | 28.86 |
| All OPIS Sessions | 33.35 | 45.24 | 78.59 | 19.52 | 19.70 | 39.22 |
| OPIA-1 | 39.88 | 44.30 | 84.19 | 25.19 | 23.95 | 49.14 |
| OPIA-2 | 51.45 | 48.73 | 100.19 | 20.85 | 22.33 | 43.19 |
| OPIA-3 | 43.55 | 45.39 | 88.94 | 36.92 | 35.92 | 72.84 |
| All OPIA Sessions | 44.96 | 46.14 | 91.10 | 27.65 | 27.40 | 55.06 |

Table VI: Diversification/Risk Taking Tendencies and Profits

| Treatment | Diversifiers' Trading Profit* Average (Std. Dev.) *obs.* | Others' Trading Profit* Average (Std. Dev.) *obs.* | Risk Takers' Trading Profit* Average (Std. Dev.) *obs.* | t-test for Difference in Means between Diversifiers' and Risk Takers' Trading Profits* Difference *t-statistic* (Prob>\|t\|) |
|---|---|---|---|---|
| | 33.41 | 4.27 | -102.68** | 136.09** |
| | (472.07) | 331.14 | 410.14 | *3.5604* |
| Baseline | *572* | *117* | 191 | (0.0004) |
| | 15.54 | -41.25 | -14.33 | 29.87 |
| Direct Portfolio | (369.61) | (406.76) | (469.44) | *0.6758* |
| Trading | *270* | *60* | *120* | (0.4996) |
| | 15.16 | 11.82 | -98.36** | 113.52** |
| | (326.87) | (154.40) | (245.58) | *2.5742* |
| Short Sale | *315* | *74* | *61* | (0.0104) |
| | 43.26 | -111.22 | -73.37 | 116.63** |
| | (525.58) | (475.25) | (518.86) | *2.0172* |
| Arbitrager | *280* | *54* | *116* | (0.0444) |

*Trading profits are the difference in expected value between the final portfolio and the initial portfolio of the trader including cash on hand and certificates

**Significantly different from zero at the 95% level of confidence.

Table VII: Frequency of rejection of the null hypothesis that final risk holdings are independent of endowments according to $\chi 2$ tests

| Session | Number of rejections at the 90% level of confidence | Number of rejections at the 95% level of confidence |
|---|---|---|
| OPI-1 | 5 | 5 |
| OPI-2 | 3 | 2 |
| OPI-3 | 6 | 4 |
| OPI-4(m) | 6 | 5 |
| OPI-5(e) | 2 | 2 |
| OPI-6(r) | 7 | 5 |
| OPI Average | 4.833 | 3.833 |
| OPIP-1 | 6 | 4 |
| OPIP-2 | 4 | 3 |
| OPIP-3 | 5 | 4 |
| OPIP Average | 5.000 | 3.666 |
| OPIS-1 | 3 | 1 |
| OPIS-2 | 5 | 4 |
| OPIS-3 | 7 | 2 |
| OPIS Average | 5.000 | 2.333 |
| OPIA1 | 8 | 6 |
| OPIA2 | 3 | 3 |
| OPIA3 | 6 | 5 |
| OPIA Average | 5.667 | 4.667 |
| Overall Average | 5.067 | 3.667 |
| Expected Frequency | 1.000 | 0.500 |
| Ratio of Actual to Expected Frequency | 5.067 | 7.333 |

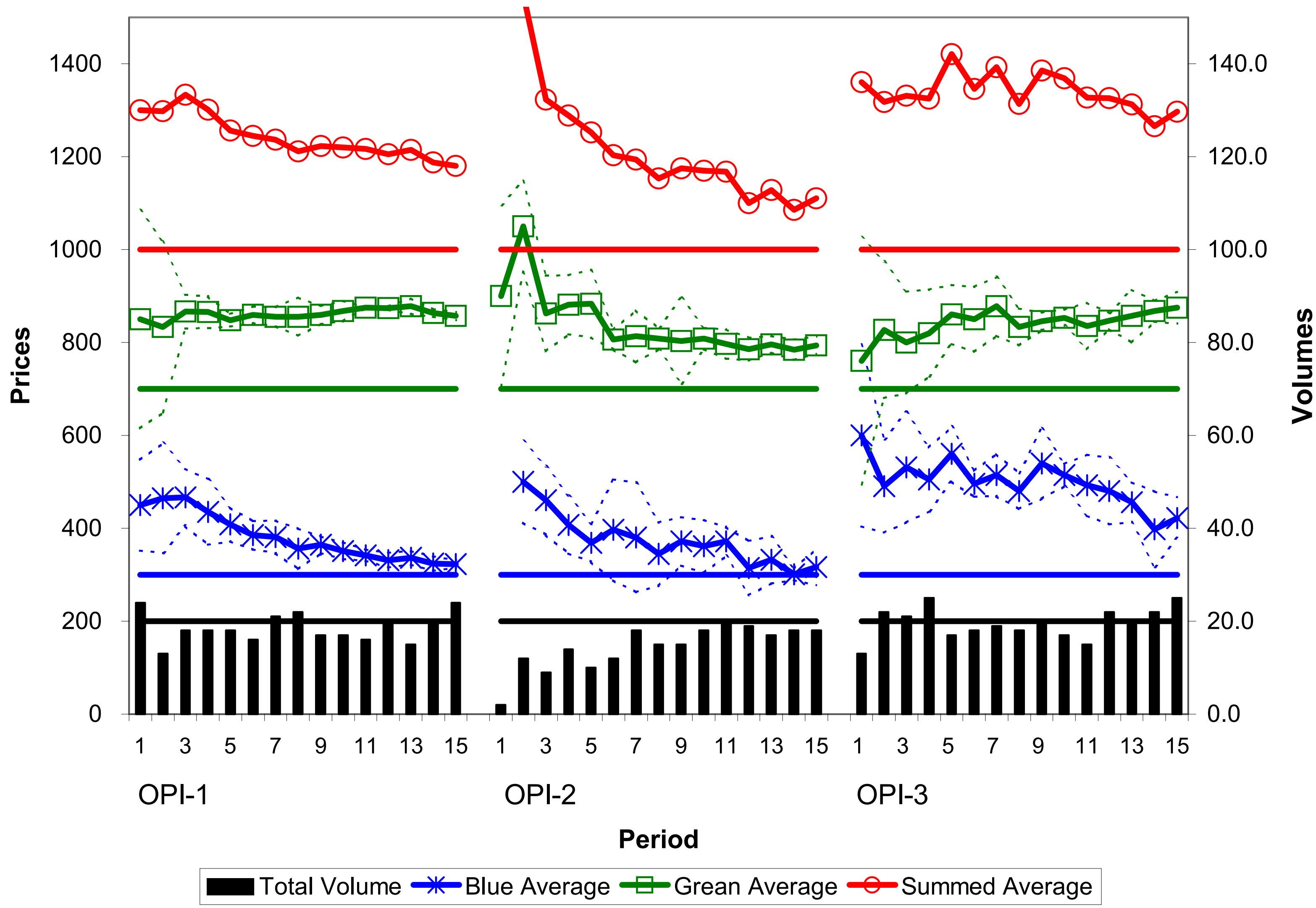


Figure 1a: Average Prices and Total Contract Volumes by Session and Period. OPI (baseline) Sessions. (Dotted lines represent +/- 2 standard deviation confidence intervals. Heavy lines represent predictions.)

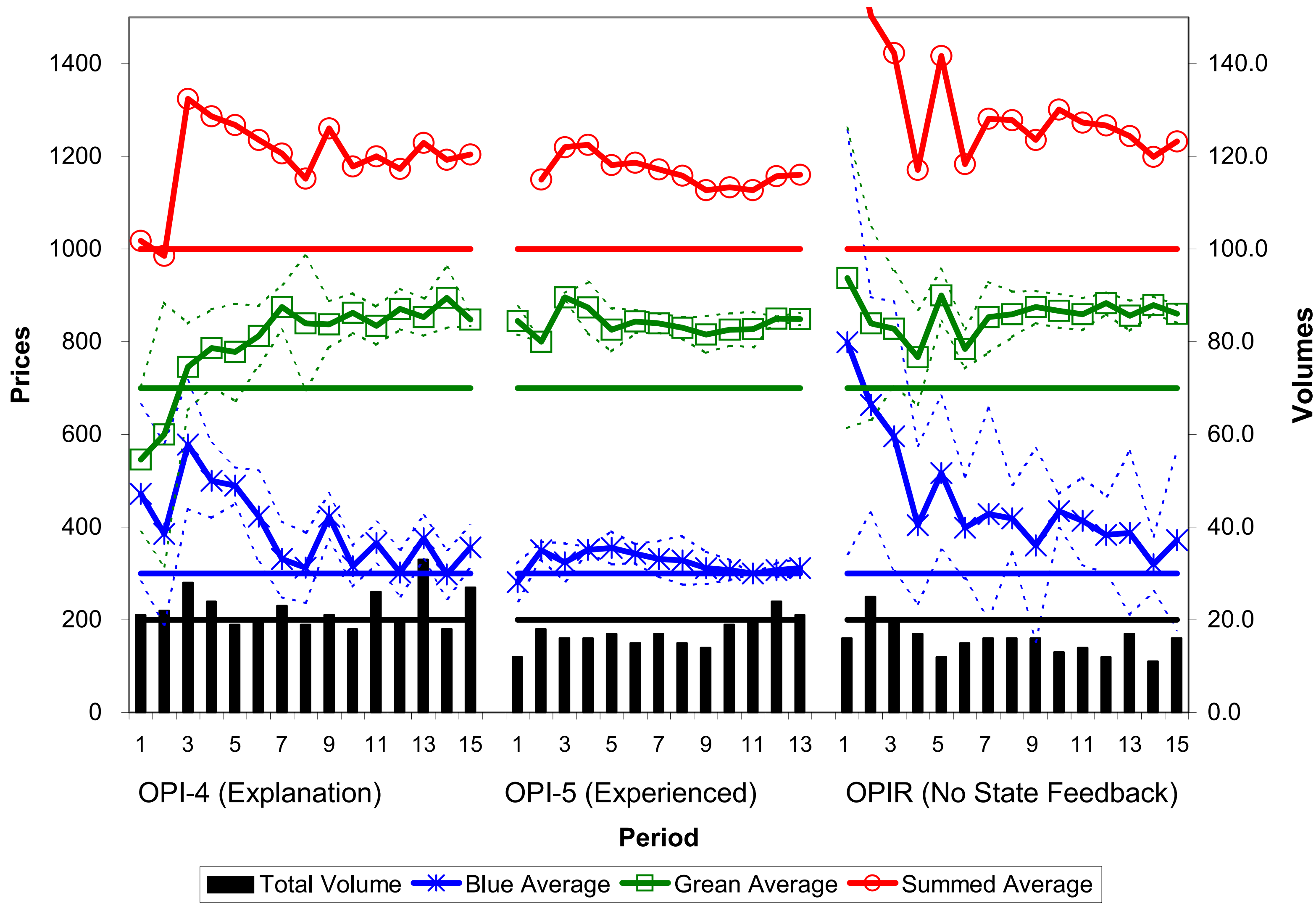


Figure 1b: Average Prices and Total Contract Volumes by Session and Period. OPI (with small design changes) Sessions. (Dotted lines represent +/- 2 standard deviation confidence intervals. Heavy lines represent predictions.)

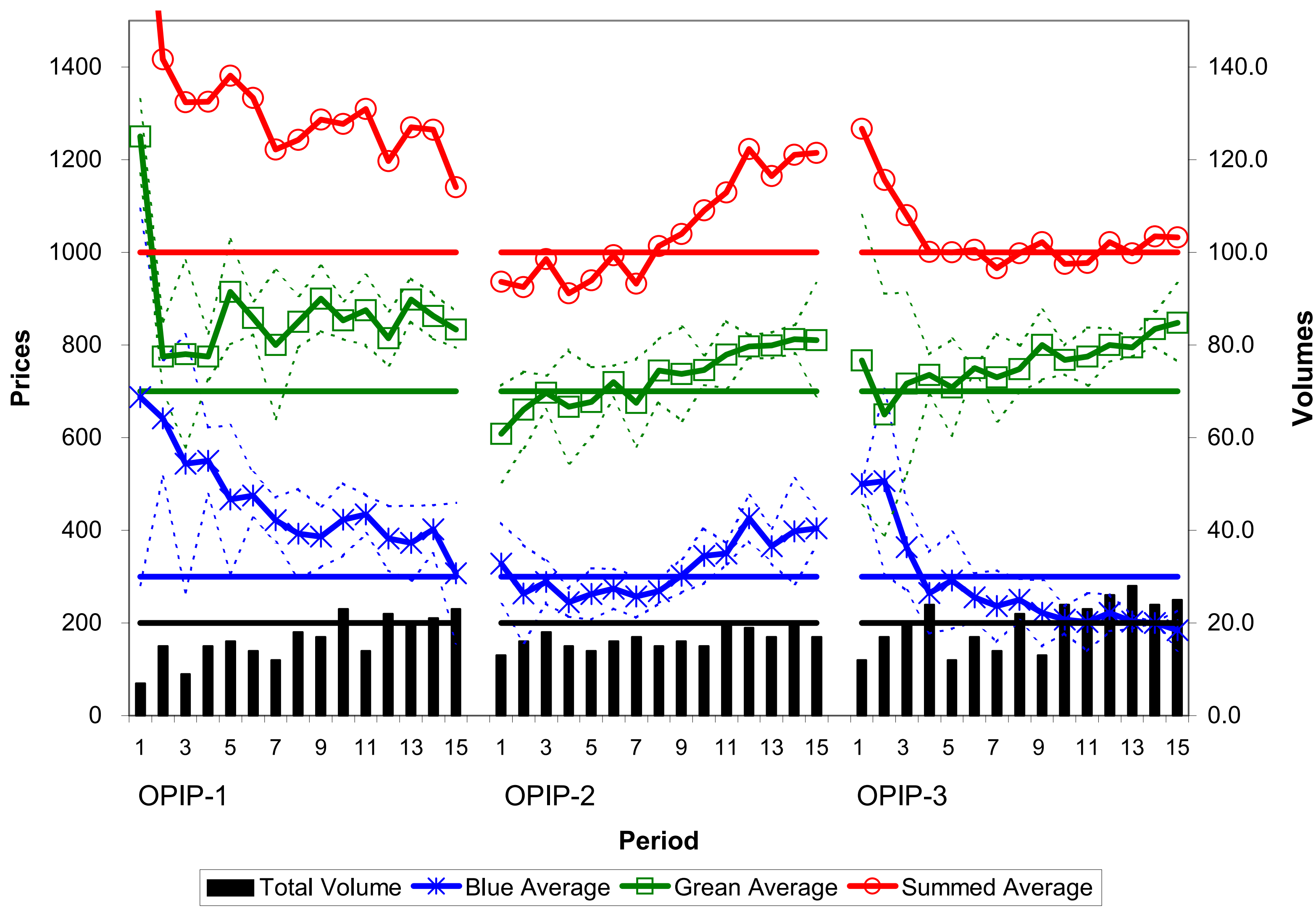


Figure 1c: Average Prices and Total Contract Volumes by Session and Period. OPIP (direct portfolio trading allowed) Sessions. (Dotted lines represent +/- 2 standard deviation confidence intervals. Heavy lines represent predictions.)

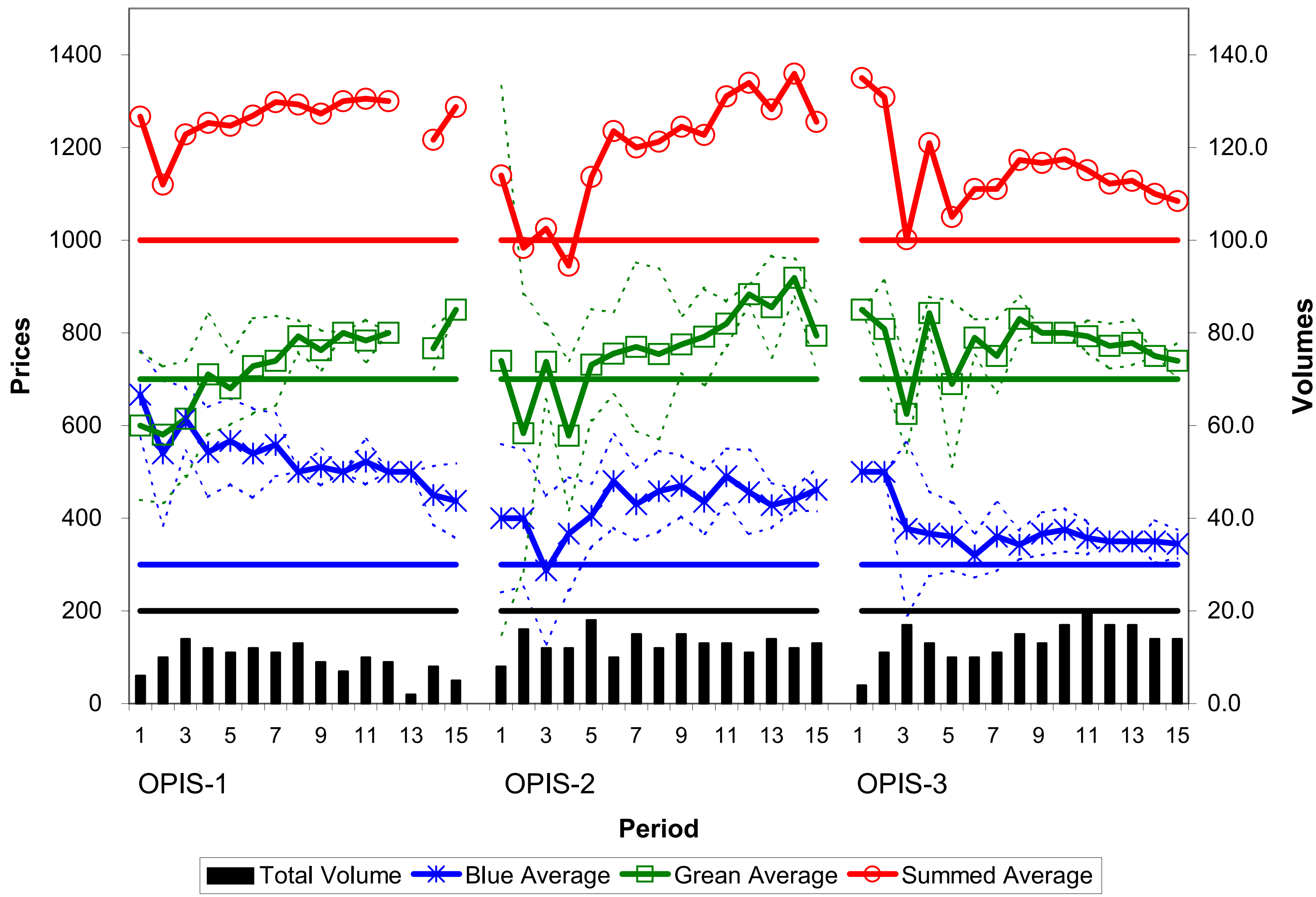


Figure 1d: Average Prices and Total Contract Volumes by Session and Period. OPIS (short sales allowed) Sessions. (Dotted lines represent +/- 2 standard deviation confidence intervals. Heavy lines represent predictions.)

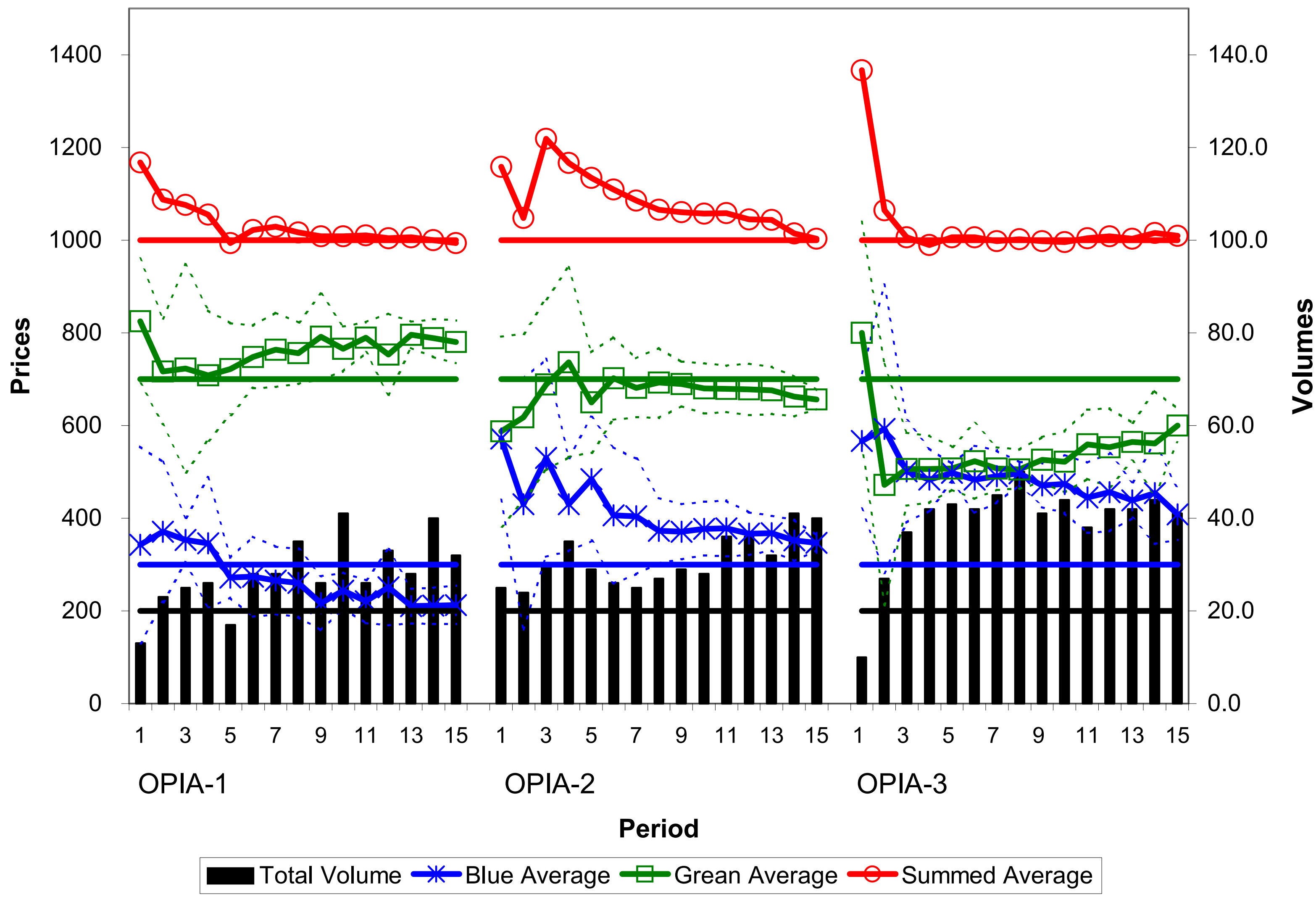


Figure 1e: Average Prices and Total Contract Volumes by Session and Period. OPIA (arbitrage opportunities exploited by experimenter) Sessions. (Dotted lines represent +/- 2 standard deviation confidence intervals. Heavy lines represent predictions.)