EXPERIMENTS

IN

INTERNATIONAL FINANCE

By

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Abstract

This thesis contains three essays that are intended to be independent works. The essays all relate to applications of experimental methods to issues of international finance. The issues of experimental finance investigated are Rate of Return Parity and Currency Crises. The first essay investigates Rate of Return Parity using a laboratory environment in which two double auction asset markets are run simultaneously. Rate of Return Parity can then be used to predict the relative price of the assets in the two markets. The results of this experiment show that Rate of Return Parity is observed when assets are very similar and the exchange rate between the currencies in which the asset markets are denominated is perfectly fixed. The degree of Rate of Return Parity is reduced as the assets become dissimilar, or the exchange rate between currencies becomes unstable. The second essay employs robot asset traders to investigate some of the behavioural rules that subjects may have been using in the simultaneous asset markets of the first essay. The goal of the robot traders is to generate data that is qualitatively similar to that of the data generated in the experiment presented in the first essay. Of the various robot populations considered, profit maximizing robots that employ a weighted trend function in calculating the value of the asset combine with a single arbitrageur produce data that is most similar to that of human subjects. The third essay examines a laboratory environment in which a currency crisis is possible but not guaranteed. This was done using an environment similar to the one used to investigate Rate of Return Parity, with a fixed and known amount of reserves with which the fixed exchange rate would be defended. In the laboratory environment the exchange rate would change if the reserves fell to zero. In this manner whether or not there was a change in the exchange rate was completely under the control of the subjects. Results indicate that subjects are able to generate currency crises based on self-fulfilling prophecies. Overall the work of this thesis indicates that care should be taken when applying Rate of Return Parity to complex environments, and that the commitment of a central bank to defending a fixed exchange rate has an important role to play in determining if a currency crisis will occur.

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Table of Contents

List of Illustrations and Figures

Chapter One

Experiments in International Finance

Chapter One

I. Introduction

A. Rate of Return Parity

One of the central issues involved with international financial markets is the movement of capital across international borders. In the simplest macroeconomic models, one of two assumptions is generally made. Either capital is assumed to be perfectly mobile between countries or capital is assumed to be perfectly immobile between countries. As students progress in their study of macroeconomics they generally find that capital is increasingly assumed to be perfectly mobile across international borders [Pastine 2000, Chang et al. 1999, Elliot and Fatas 1996]. Moreover in many cases the failure of field data to provide significant support for the predictions of perfect capital mobility is attributed to impediments to the free mobility of capital [Obstfeld and Rogoff 2000, Feldstein and Horioka 1980].

This of course raises the question; how mobile is capital across international borders? One of the most commonly used ways of examining this problem is to examine one of the major predictions associated with the assumption of freely mobile international capital. If capital is in fact freely mobile across international borders, then capital should flow from areas of low return to areas of high return. Consider a situation in which the return on capital in Country A was 10% and the return on capital in Country B was 5%. One would expect that those people who were investing in Country B would move their capital to Country A, if they were free to do so. If this assumption of the behaviour of investors holds along with the assumption of decreasing marginal returns to capital investment, any difference in the rates of return on capital between countries would be resolved by the flow of capital from one country to another until the return on capital investment in both countries was equal. Typically, this theory is considered in terms of government assets with known values at maturity. This result as applied to these specific assets is referred to as interest rate parity . There is a more general parallel to interest rate parity which can be referred to as rate of return parity. Rate of return parity refers to the equating of the rate of return on assets in general, rather than specific government issued assets. Either of these conditions can also be characterized as the outcome of traders taking advantage of all arbitrage opportunities.

Much of the investigation of the free flow of capital has focussed on this prediction, either as Covered or Uncovered interest rate parity. Covered interest rate parity refers to a situation in which investors use a forward market to avoid exchange rate risk. Uncovered interest rate parity refers to a situation in which exchange rate risk is not avoided in this manner. Investigations of interest rate parity focus on the government set interest rate in order to avoid difficulties associated with degrees of risk in different countries and with different investments. Covered interest rate parity has met with a fair degree of support in this type of research [Holmes 2001]. Uncovered interest rate parity has met with considerably less support. There are two possible explanations of this result. First, capital is not sufficiently mobile for uncovered interest rate parity to hold. Second, that the assumptions on which the theories are based are incorrect.

Another approach to the issue is less direct. If capital is in fact freely mobile between countries, the level of investment and the level of saving in a country will be uncorrelated. If a country has a high level of savings and capital is freely mobile there is no reason to expect that a significant proportion of the savings will be invested in the home country. In 1980, Feldstein and Horioka attempted to address this issue. Using data from the major industrialized countries they calculated the degree of correlation between the domestic savings rate and the domestic investment rate for each of these countries. In all cases the result was a correlation estimate that was very close to 1, as opposed to being very close to zero. These results indicated to many, including the authors, that capital did not move freely across international borders during the time frame of their data set.

One of the major problems encountered in both of these approaches to testing the mobility of capital, as well as interest rate parity and rate of return parity, has been the possible influence of exchange rate risk. If the value of a foreign currency in terms of the domestic currency is uncertain over the life of the investment it may then be that investors will avoid the exchange rate risk by investing domestically.

Another major problem encountered by researchers of international capital mobility is that reliable data on many potentially important factors are unavailable. In examining the predictions of capital mobility, any factor that may influence the mood and beliefs of investors is relevant. The list of things that potentially could influence the mood and beliefs of investors is long and not always readily quantifiable.

Addressing the degree of capital mobility in relation to international borders is important for understanding international finance. The predictions of even the most basic of models are greatly influenced by the degree of international capital mobility. Even in introductory macroeconomics classes students learn of the importance of the degree of capital mobility. The standard example is viability of monetary policy under a fixed exchange rate regime. In this simple model, monetary policy is viable if capital is immobile. If capital is perfectly mobile on the other hand, monetary policy becomes impotent [Mankiw and Scarth 2001].

A further impetus for considering the validity of interest rate parity is that it is often assumed in building models of other phenomena of international finance, specifically currency crises. With the empirical support for covered interest rate parity and the lack of support for uncovered interest rate parity one begins to wonder if freely mobile capital is the issue at all. In addition to the dichotomy of empirical support for covered and uncovered interest rate parity are a number of models in which the high degree of correlation between national investment and savings rate can be explained even if capital is assumed to be freely mobile.

Models which are developed to help our understanding of the emergence of currency crises and help develop policies for controlling the effects of currency crises tend to incorporate the assumption that uncovered interest rate parity characterizes their abstract environments. However, the empirical evaluations of the prediction of uncovered interest rate parity are frequently not supported. This makes the unquestioned inclusion of uncovered interest rate parity into the more complex models dubious. As the attempts to identify uncovered interest rate parity empirically are confounded by many variables for which it is difficult to control after-the-fact with statistical techniques, the use of a controlled laboratory environment may provide an opportunity to evaluate rate of return parity in environments with and without exchange rate risk and with perfect capital mobility. If an evaluation in the controlled laboratory environment which permits the exercise of all arbitrage opportunities, provides support for rate of return parity, its inclusion into the more complex models is less questionable.

B. Currency Crises

In the late 1990s the world was re-introduced to currency crises through the "Asian Crises".[1] A currency crisis occurs when a country's central bank is no longer able to support the previously fixed exchange rate and must either allow the exchange rate to float (be determined solely be the market) or devalue the fixed exchange rate. The costs of such an event can be enormous. In one case, the central bank of Korea spent approximately 58 billion US dollars defending its fixed exchange rate prior to its collapse in 1997 [Zalewski 1999]. This figure does not begin to take into consideration the impact of the currency crisis on the Korean economy at large.

Compared to the potential impact that a currency crisis can have on a country, such events are not well understood. In looking to economic research for direction in the face of a potential currency crisis, policy makers are confronted with a dichotomy. One class of research, based on Krugman [1979], focusses on fundamental values in explaining currency crises. In this line of thinking a currency crisis is caused solely by an inconsistency between the level at which the country's exchange rate is fixed and the fundamental or market value of the currency. The direction this model gives to policy makers is clear, domestic monetary policy and the level

[1] In 1997, five East Asia Countries experienced currency crises: Indonesia, Malaysia, the Philippines, South Korea, and Thailand.

of the fixed exchange rate must be consistent for the fixed exchange rate to survive for any length of time.

A second line of research argues that the fundamentals theory of exchange rate crises does not fully explain some of the historical instances of fixed exchange rate collapse. The collapse of the Korean Won in 1997 is an example. Prior to the currency crisis Korea had neither a grossly over-valued currency nor a substantive balance of payments deficit, yet this country still was subject to a currency crisis. Several authors have argued that the fundamentals of the Korean economy were not as weak as the fundamentals in other countries whose currencies did not collapse [Zalewski 1999, Woo et al. 2000, Liew 1998, Wirjanto 1999, and Yoo and Kim 1998].

This second line of research suggests there may be multiple equilibrium exchange rates, each supported by a set of self-fulfilling expectations. An equilibrium with a high exchange rate is stable so long as all investors hold the expectations that support it. If investors' expectations change then a different and lower exchange rate prevails.

Before relying on these models for policy guidance, however, it would be comforting to know that the behaviour and outcomes they describe can be shown to exist. Once again, laboratory experimentation may serve as a useful bridge between abstract theory and the complexity of the field.

The research presented in this thesis represents one of the first organized attempts to apply laboratory experimental methods to problems of international finance. The issues surrounding international finance make using field data unsatisfying in many different occasions. Issues of rate of return parity and currency crises have confounded many researchers attempting to link abstract theory with data from international financial markets. The major difficulty such researchers must address is the complexity of the data. There are a myriad of potentially relevant factors when considering the behaviour of investors and international financial markets. Even the weather can have a meaningful impact on the mood of investors and consequently the behaviour of international financial markets.

By recreating a simplified version of international financial markets in the laboratory some of the confounding issues described above can be avoided. The behaviour of exchange rates and potential dividends are known quantities in a laboratory environment, whereas these quantities would be unknown in the field. Thus exploring issues of rate of return parity and currency crises in laboratory allows for a wider range of systematic exploration than would be possible in the field. If it is impossible to generate the type of behaviour predicted by theories of rate of return parity and currency crises in a controlled laboratory environment, there is little reason to expect that this behaviour would be observed within the complex milieu of the real world.

These experimental investigations do not represent an exhaustive approach to the issues of rate of return parity or currency crises. These investigations are only a starting point for research in this area. There are many more questions that need to be addressed in the areas of rate of return parity and currency crises. This research is intended to lay the ground work for future investigations of rate of return parity and currency crises and other issues relating to international finance as well as to demonstrate that the tools of experimental economics can be applied to problems of international finance.

The following three research essays are an attempt to begin to understand these important issues of international finance. The important issues are rate of return parity and currency crises. The first essay uses a laboratory experiment to examine the emergence of rate of return parity with human subjects in simultaneous asset markets, with no impediments to arbitrage. The second essay utilizes the same environment but it is populated by robot traders that engage in market activities in accordance with known behavioural rules. The objective of this essay is to establish some of the possible behavioural rules followed by human subjects who participated in the experiment presented in the first essay. The third essay examines a laboratory experiment in which human subjects have the opportunity to cause a currency crisis. As these essays are intended to "stand alone" there is some repetition in their introductions. In spite of being intended to stand alone, the essays share common goals. The first and most direct is to provide the understanding and opportunity to examine currency crises in a controlled laboratory environment. As the relationship between two asset markets is not perfectly understood when there is no possibility of an exchange rate collapse, this provides a natural starting point for the laboratory investigation. Once a greater understanding of the link between separate simultaneous asset markets has been achieved, an exploration of currency crises can be undertaken. The second less direct goal of these essays is to demonstrate that laboratory experiments can be meaningfully applied to issues of international finance. Each of the three essays are described in slightly more detail below.

II. The Essays

A. Rate of Return Parity in Experimental Asset Markets.

Rate of return parity is a core hypothesis of the links between different asset markets.

Though generally unproven, the assumption of rate of return parity and, implicitly, perfect capital mobility, is central to current research in international finance.[2] There has been no shortage of attempts to empirically support or disprove rate of return parity with data from financial markets (Chapter Two presents a description of some this work). On the whole, analysis of these data has been inconclusive after various modifications to the theory have been tested. To further complicate the issue there are some policies in place that actively prevent the free movement of capital, which would prevent researchers from observing interest rate parity in field data. Ascertaining the impact of these policies on the mobility of capital requires a counterfactual which is very difficult and costly to do with actual economies and financial markets. Moreover, it is almost impossible to know which variables are relevant in the pricing of assets. To overcome these issues and others described in the next chapter an alternate data source is needed. Ideally this alternate data source would avoid any restrictions on the movement of capital, allow the researcher to observe all relevant variables, and limit the potentially confounding factors such as exchange rate risk. To this end, controlled laboratory experimentation is used. Subjects recruited from the McMaster University student population participated in two simultaneous asset markets. Each asset paid dividends and was priced in its own currency (denoted Blue Dollars and Red Dollars). In various treatments of the experiments the two assets had different characteristics. In the base treatment both assets had identical expected dividends and identical variances in expected dividends. If subjects do not behave in a manner consistent with the rate of return parity prediction in this simplified environment there

[2] Readers should be aware that a special case of rate of return parity, referred to as covered interest rate parity has been strongly supported in empirical research. There has been little support for uncovered interest rate parity with rational expectations.

is little hope that capital is sufficiently mobile or arbitrage is sufficiently complete to induce the predicted result in the real world. Throughout this treatment the exchange rate between the currencies in which the assets were denominated remained fixed with certainty.

The remaining four treatments used in the experiment were designed to test the robustness of the rate of return parity result if the prediction was supported in the base line treatment. If rate of return parity is supported in the base line treatment it will then be important to establish whether increasingly complex environments are likely to cause rate of return parity to fail. Accordingly the second treatment held the expected values of the two assets equal while allowing one asset's dividends to be subject to a higher variance. This treatment was intended to capture the impact of risk on rate of return parity. The third treatment dealt with assets that had the same variance in dividends, but one asset had a higher expected dividend. This slightly more complex environment was designed to test the robustness of the rate of return parity relationship in the face of assets that were fundamentally different. The fourth treatment involved assets that had different expected dividends as well as different variances of dividends. This treatment was designed to further test the general robustness of the interrelation of the two asset markets. The final treatment in this investigation involved assets with different expected dividends, the same variance of dividends but were connected by an exchange rate that was subject to probabilistic devaluation. This treatment was designed to test the viability of the rate of return parity relationship in the face of explicit exchange rate uncertainty. If rate of return parity survives these treatments, there is reason to believe that more complex models of international financial systems which assume the truth of rate of return parity have a sound foundation.

The experimental results provide substantial support for rate of return parity in the simple treatments, even when the behaviour of subjects generates price bubbles. The degree of support for rate of return parity is diminished as the assets in question become more and more different. Once exchange rate risk is introduced, the experimental results offer little support for rate of return parity.

B. Robot Traders

The second essay furthers our understanding of how individual subjects may behave. It was initially difficult to understand how subjects could behave in a manner that would generate price bubbles while maintaining a definite link between the two asset markets. This question led to the development of the robot asset traders investigation. In this investigation different types of robot asset traders generate price data that conform to the qualitative aspects of the price data from the first treatment of the experiment presented in the first essay. In designing the rule for robot traders which will generate bubbles and crashes and preserve rate of return parity we are able to gain insight into the motives which may characterize the human traders in our laboratory markets. This, in turn, may help us understand behaviours in actual asset markets.

Five different types of robot traders are employed in this investigation. The first type is based loosely on the zero intelligence robot traders developed by Gode and Sunder [1993]. These robots are dubbed "zero intelligence" because they employ no strategy beyond an unwillingness to buy or sell at a loss. In the robot sessions conducted by Gode and Sunder [1993] each robot is assigned either a redemption value or a production cost, but not both. This is very similar to the process through which redemption values and production costs are assigned to human subjects in market experiments. The zero intelligence traders used in the robot sessions reported in this essay differ in two important ways. The first difference is that these traders are not directly assigned values, instead each trader is assigned a randomly generated risk attitude. The robots then use this risk attitude and the dividend structure to calculate the value of the asset at each point in time. The second difference is that all traders are able to act as buyers and sellers. Robots randomly choose which market to take an action in and then randomly choose to enter a bid or an ask. If the robot chooses to bid, a random bid is generated between the outstanding bid, if any, and the robot's asset value. If the randomly generated bid is greater than the outstanding ask, a transaction takes place at the price of the outstanding ask. If the robot chooses to ask, a random ask is generated between the outstanding ask and the robot's asset value. If the randomly selected ask is lower than the outstanding bid a transaction takes place at the price of the outstanding bid.

The second type of robot trader is an adaptive-expectations trader. These traders calculate their initial values for the asset in exactly the same way as the zero intelligence robots. The process for choosing to enter a bid or an ask is also the same. Once these priors are calculated these robots then use a standard type of adaptive expectations updating procedure to calculate the value of the asset at each point in time. These values will converge to some common value as transactions take place. The goal of this type of robot trader was to demonstrate that adaptive expectations alone cannot generate the price bubbles and crashes observed in human populated asset markets.

The third type of robot chooses between bids and asks in exactly the same way as the previous two types. The difference between this type of robot and the those above is how the values robots use change as the session progresses. These robots calculate the value of assets based on a weighted average of the risk-adjusted dividend value and a trend component. These robots are referred to as trend-based traders. The trend term is included in order to generate data with price bubbles and crashes.

The fourth type of trader is one that chooses its actions based on a profit maximization criteria. The asset values used by this type of robot are the same as those used by the trend-based traders. These robots choose whether to bid or ask based on the profitability of randomly selected bids and asks. The purpose of this type of robot trader is to examine whether the rate of return parity observed in human populated markets can be explained by profit maximizing behaviour without an explicit form of arbitrage.

The fifth type of trader was an arbitrageur. This arbitrageur would only be active if there existed opportunities for immediate arbitrage. The arbitrageur always participated in markets with 9 random-choice trend-based robot traders type three or 9 profit maximizing trend-based traders type four. If the outstanding bid for one asset was higher than the outstanding ask for the other asset the arbitrageur would sell an asset at the price of the high outstanding bid, transfer the funds to the market with the low outstanding ask and purchase the asset in question. In those cases in which the arbitrageur did not hold any of the asset with the high bid they simply purchased the asset with the low ask. It was unclear how effective a single arbitrageur would be in market populated by unsophisticated agents.

If a single arbitrageur can induce rate of return parity in this type of asset market it is a strong indication that failure to observe rate of return parity in field data may be caused by barriers to full arbitrage.

Intriguingly, the results of these simulations indicate that human subjects likely needed only a single individual acting as an arbitrageur to produce substantial support for rate of return parity. Further, to generate finitely lived price bubbles, robots had to include a trend term in their valuation of the asset in question with increasing weight on the fundamental value of the asset. While by no means an exhaustive exploration of possible behaviours, the simple behavioural rules employed by robots help us understand the emergence of rate of return parity in simple multiple asset environments.

C. Currency Crises in Experimental Asset Markets

The third essay represents one of the first attempts to explore currency crises in a controlled laboratory environment. Currency crises have long been problematic for those attempting to understand how exchange rates work. The currency crises of East Asia in the late 1990s renewed interest in the potential causes of currency crises for nations that were seemingly economically vibrant. Much of the current debate over currency crises concerns what role, if any, self-fulfilling prophecies play in these situations. This is an important debate. If there is no role for self-fulfilling prophecies in currency crises, the policy prescription is relatively simple: maintain consistent monetary and exchange rate policies. Thus any government attempt to maintain a fixed exchange rate and expansionary monetary policy will almost certainly encounter difficulties in maintaining the fixed exchange rate. If, on the other hand, there is a prominent role for self-fulfilling prophecies, prescribing policy is much more difficult. In this situation, policy prescription requires influencing the beliefs of individuals.

To assess the role that self-fulfilling prophecies play in currency crisis a comparatively simple laboratory environment is constructed. The basis of the environment is identical to that employed to investigate rate of return parity: dual simultaneous asset markets denominated in separate currencies. The difference between the environment constructed for this experiment and that which focussed on rate of return parity is that the exchange rate is not fixed with certainty, nor is it subject to random devaluations. Instead, one currency (Red Dollars) is treated as a reserve currency with which the other currency (Blue Dollars) is to be defended. Every time Blue Dollars are exchanged for Red, reserves of Red Dollars fall. If the reserves are ever exhausted, the exchange rate depreciates. All subjects in this experiment were paid based on the value of their holdings of Blue and Red Dollars, converted to the (potentially devalued) Blue currency. Thus participants holding the Red currency profit from a devaluation. If participants believe that the Blue currency is likely to be devalued they have incentive to convert their Blue Dollars to Red. If they all do this, devaluation will occur. On the other hand if participants believe the Blue currency is secure, they have no such incentive and devaluation will not occur. Thus this environment admits two equilibria: one in which the Blue currency is devalued and one in which the Blue currency's value can be sustained.

There were two treatments in this experiment. The treatment variable is the initial size of the reserve with which the fixed exchange rate is to be defended. In one treatment the initial reserves of Red Dollars were set at 50% of the initial endowment of Blue Dollars held by subjects. In the other treatment the initial reserves of Red Dollars were set at 100% of the initial endowment of Blue Dollars. Four sessions of each treatment were conducted.

If there are any sessions in which the reserves are exhausted this experiment will provide evidence that self-fulfilling prophecies play a role in currency crises. In this environment there is no consistent balance of payments deficit to guarantee that a crisis will eventually occur. If there appears to be some systematic manner in which the reserves are exhausted then the evidence in favour of an important role for self-fulfilling prophecies will be strong indeed.

III. Conclusions

Each of the three essays in this thesis has an important role to play in improving our understanding of international finance. The essay embodied in Chapter Two is a search for rate of return parity under idealized conditions but with inexperienced and non-expert subjects. Failure to observe rate of return parity in this situation would not mean that rate of return parity is impossible in the field, as field markets are populated by experienced professional traders. Observation of rate of return parity in this environment is in fact conclusive, however. If inexperienced non-expert traders produce the rate of return parity result, it is reasonable to believe that experienced professional traders will produce similar results in the field.

The essay presented as Chapter Three of this thesis is important in two ways. First it represents a possible bridge between the use of simulation and experimentation. By attempting to re-create the observed behaviour of human subjects, simulation can offer a meaningful testing ground for theories of human behaviour. Second, it demonstrates the importance of arbitrage to rate of return parity and capital mobility as a designated arbitrageur is required to generate results that mimic the qualitative characteristics observed in Chapter Two.

Chapter Four builds on the results of Chapter Two. Chapter Four presents the first attempt to examine currency crises in a laboratory setting. This essay examines a laboratory environment in which a currency crisis is possible but no guaranteed. By examining the behaviour of subjects in this environment a great deal of insight can be gained into the mechanics of currency crises and the support for rate of return parity in the face of such events.

While written to stand alone as much as possible, the three main essays of this thesis are definitely part of a single research program. Specifically, Chapters Three and Four rely heavily on the findings of Chapter Two. With this in mind the readers are invited to turn their attention to Chapter Two entitled, “Rate of Return Parity in Experimental Asset Markets”.

Chapter Two

Rate of Return Parity in Experimental Asset Markets

Chapter Two

Rate of Return Parity in Experimental Asset Markets

I. Introduction

The theories of international macroeconomics are quite diverse. They range from simple Keynesian models of open economies to modifications of the Mundell-Fleming small open economy and more recently to Real Business Cycle models. Whether considering international capital flows in monetary economics, modelling currency crises, or proving the impotence of monetary policy with fixed exchange rates, one simple and seemingly innocuous assumption is made time and time again. The assumption is that international capital markets are integrated in such a way that arbitrage is complete so that the rate of return on an asset in one country will equal the rate of return on a similar asset in another country once expected changes in the exchange rates are taken into consideration. The realization of this result is given the name of interest rate parity and is often expressed as

$$i = i^* - E(\Delta e) \qquad (2.1)$$

where i is the domestic interest rate, i* is the foreign interest rate, E is the standard expectations operator, and Δe is the percentage change in the exchange rate between the domestic and foreign currencies. The same idea can be applied to more general asset markets, and for the purposes of this essay this will be referred to as rate of return parity. In such a case *i*, in equation (2.1), represents the rate of return on investing in a domestic asset and *i** would represent the rate of return on a comparable foreign investment.

Given the prominence of the assumption of this outcome in open economy macroeconomics, it is reasonable to be concerned with its validity. The most obvious source for confirmation of this outcome is empirical work using field data from international capital markets. Uncovered rate of return parity has met with little support from studies of field data, as the sources below indicate. A number of reasons for the lack of support for uncovered interest rate parity and rate of return parity have been proposed. These can be grouped into several categories. First is a lack of international capital mobility. Second is trade friction in international markets. Third is that the models of asset pricing used are incorrect. The fourth is that the expectations process assumed does not fully capture the expectations of agents. Fifth is that agents require a risk premium to be paid on investments denominated in unstable currencies and thus rates of return will be separated by a risk premium.

Some of the strongest evidence that capital does not flow freely across international borders is provided by Feldstein and Horioka [1980]. They show that there is a high degree of correlation between the domestic savings rate and domestic investment. If capital did flow freely between countries the correlation would be close to zero. Baxter and Cruncini [1993] have shown that it is possible to observe high savings and investment correlations in a real business cycle model in which perfect capital mobility holds. Thus Feldstien's and Horioka's finding may not indicate a lack of capital mobility but some other phenomenon.

Obstfeld and Rogoff [2000] provide an argument that the observation of high correlation and failure to support uncovered rate of return parity may be driven by trade frictions. If trade frictions are in fact at the root of the observed connection between domestic savings and investment rates, an environment in which there are no trade frictions will observe a high degree of capital mobility as well as uncovered rate of return parity.

When considering the issue of uncovered interest rate parity, a mis-specification of the underlying model is cited as the problem, as in Cox et al. [1981] and Franchot [1996]. The original specification of interest rate parity in the opinion of these researchers was incorrect due to an inconsistency with the underlying model of asset pricing with respect to the term structure of interest rates. The respecified interest rate parity relationship has met with more support in empirical testing at the cost of simplicity. If there is an inconsistency with the underlying model of asset pricing, Equation (2.1) does not capture the true relationship between foreign and domestic assets.

Some researchers have attempted to explain the lack of support for uncovered interest rate parity in field data as arising from errors in expectations [Frankel and Froot 1987, Froot and Frankel 1989]. Many of the tests of uncovered interest rate parity have relied on the assumption of rational expectations of changes in exchange rates. If individuals do have rational expectations, the expected value of a variable in period t+1 formed at time t can be replaced in the data set by the actual value of the variable in time t+1 plus a white-noise error term. If rational expectations do not describe the expectations held by agents then explicit modelling of the expectation process becomes necessary and the expectations term in Equation (2.1) must be replaced with an explicit model. An adaptive expectations model is one example of a potential replacement for $E(\Delta e)$ in Equation (2.1).

Another approach to dealing with the observed lack of support for uncovered interest rate parity has been to test for real interest rate parity. In this line of reasoning, the simple rate of return parity relation is confounded by differences in inflation rates and other factors. The simple model of rate of return parity as expressed in Equation (2.1) assumes that any impact of inflation in the system will be absorbed by the expected change in the exchange rate. This may not be the case. This approach to the problem has been tested by many researchers. Dutton [1993] and Gregory [1987] find some support for real interest rate parity, while Fraser and Taylor [1990] reject the hypothesis of RIRP using more advanced econometric techniques. Once again we can see that there is conflicting evidence on the issue of uncovered rate of return parity.

Another possible explanation of the failure to find support for rate of return parity in field data is the existence of an exchange rate risk premium [Fama 1984, Mayfield and Murphy 1992]. If the assumption of risk neutrality of investors implicit in Equation (2.1) is violated, then this simple expression of rate of return parity will not hold. The solution to this problem is to incorporate risk premiums into the theory and tests of rate of return parity. This means a significant modification of Equation (2.1) through the addition of a risk premium. The weakness of this approach is that it requires a strong model of risk, a great deal of information about investors and speculators, or relatively advanced econometric techniques. This approach has found some support for rate of return parity.

One method of controlling for exchange rate risk premiums without explicit modelling of risk attitudes would be to consider data from the Bretton Woods era. During this period exchange rates of major currencies were fixed with a fair degree of certainty, and therefore exchange rate risk would have been at a minimum. Tests of rate of return parity using data from the Bretton Woods era have met with more success. Aliber [1973] includes a tolerance for transaction costs before rate of return parity can be supported using simple histograms.

Even with the leeway granted by including a notion of transaction costs, there are a number of observations that cannot be explained by rate of return parity. Aliber suggests that this may be due to the risk of monetary authorities imposing capital controls. Frenkel and Levich [1975] perform a similar analysis by calculating a neutral band around strict rate of return parity due to transaction costs. They find that approximately 85% of the observations lie within their neutral band. The authors further argue that many of the observations that lie outside the neutral band are due to incomparability between the assets considered, differences in taxation across countries, different risks of assets, governmental controls, and liquidity constraints. Frenkel and Levich [1977] apply stronger econometric techniques to a wider data set which includes periods of managed floats. The findings are very similar to those of their 1975 work. Deardorff [1979] provides motivation for a one-way arbitrage condition which would significantly reduce the transaction costs and the size of the neutral band as estimated by Frenkel and Levich [1975, 1977]. Levich [1998] argues that this reduction in the size of the neutral band does not change the support for rate of return parity under the system of fixed exchange rates. This would seem to indicate that the lack of support for rate of return parity in more modern research is an artifact of flexible exchange regimes, but few authors have made this argument explicitly.

Other investigators have attempted to make use of the time series properties of the data on international financial markets. This approach focuses on rate of return parity as a long run relationship. Employing this technique means asking if the differential between two interest rates tend toward some stable relationship. With the use of vector autoregression (VAR) models and tests of restrictions, researchers such as Hunter [1992], Juselius [1995], and Taylor [1987] find that previous rejections of rate of return parity were likely due to the existence of exchange rate risk premia in the data.

From the existing literature on rate of return parity we can see that there is no general agreement as to validity of this prediction in field data, particularly in the modern period of floating and imperfectly fixed exchange rates. This lack of consensus may be caused by factors that confound the relationship between capital markets in the available field data. There are four major confounding factors in this system. The first is the difficulty in estimating expectations due to the large number of potentially relevant factors. Estimates of expectations are fraught with difficulties. Therefore the problems of estimating the expectations of the change in the exchange rate makes testing models of rate of return parity difficult. The second confounding factor is the lack of perfectly identical financial instruments. If the instruments being considered are not perfectly identical in fact and are not seen as being perfectly identical by investors, rate of return parity cannot be expected to hold. The third possible confounding factor is that of frictions in capital and goods markets. The final confounding factor is that of exogenous shocks to capital markets. International politics, prices of fundamental inputs, and the mood of investors both domestic and foreign are likely to have an impact on the viability of rate of return parity, through changes in the underlying economies.

The confounding factors mentioned above will have different impacts on different data sets and will likely have to be dealt with in different ways. Instead of attempting to address the problems ex post in field data, the alternative of surveys or laboratory experiments can be used. Rather than applying complex econometric techniques to eliminate or reduce these problems in a given data set, an environment can be designed to generate data in which these problems never arise. If rate of return parity holds in an environment in which the confounding problems do not occur, then some support can be lent to the basic principle behind both interest rate parity and rate of return parity as real phenomena.

Some researchers have attempted to use survey data to resolve some of the problems found with observations of market outcomes. Benzion et al. [1994] provide a direct attempt to capture the expectations and discount rates of individuals with respect to real assets. The results of this investigation do not support rate of return parity. The weakness of the survey approach is that individuals have very little incentive to report honestly or perform the calculations necessary to give a realistic response on a survey.

The work of Noussair, Plott, and Riezman [1997] represents an attempt to examine exchange rates and purchasing power parity in a laboratory environment. The authors created an environment in which there are incentives for trade. The environment consisted of two "countries", each with separate markets for two goods as well as a market for the currency of the two "countries". The authors conclude that the exchange rate and the prices in the currency market converge to the competitive level, while neither the law of one price nor purchasing power parity are supported by the experimental results. This means attempts to test for rate of return parity that have explicitly or implicitly assumed purchasing power parity holds [Dutton, 1993, Gregory 1987, Fraser and Taylor 1990] may be gravely in error. Hazlett and Ganje [1999] provide an extension of this environment that includes official and parallel currency markets and also find that the exchange rate converges to the competitive rate in the parallel market. Both these works focus on exchange driven by international trade.

Fisher and Kelly [2000] report the only attempt thus far to test rate of return parity in a laboratory environment in which two asset markets are open for trade simultaneously and these markets are joined by a common currency. Subjects could buy and sell either asset in double auction markets. The authors argue that the relative asset prices constitute the exchange rate in this environment, and support for rate of return parity can be observed if the relative asset prices conform to the value predicted by the nature of the two assets. This work builds on the fairly large body of literature on experimental asset markets. Sunder [1995] offers a slightly dated survey of the experimental asset market literature. One of the characteristics common to almost all experimental asset markets is the existence of price bubbles. In these experiments the price of the asset is below its fundamental (risk neutral expected dividend) value in early trading periods, rises well above the fundamental value in the middle periods of the session, and finally the price often falls back to or below the fundamental value shortly before the end of the session. These bubbles are greatly reduced in size and frequency when subjects are experienced in the environment [Smith, Suchanek, and Williams 1988].

Within this context Fisher and Kelly [2000] find both speculative bubbles and some support for rate of return parity. There are, however, some problems with the work. The design of a single currency in which trading takes place and dividends are paid may cause a higher degree of integration between the asset markets than if the markets were denominated in different currencies. In addition to this, the experimental design and implementation contain some weak elements. Specifically, in many treatments some subjects had experience in the environment while others did not and there were different numbers of sessions across treatments.

The research presented in this paper is a more systematic examination of a multiple asset environment to evaluate the prediction that rate of return parity will result when capital is freely mobile. The overarching hypothesis of this essay is that the rates of return in two simultaneous asset market will be equalized. This is the same overall hypothesis of Fisher and Kelly [2000] and the papers on rate of return parity discussed above. In short, the goal of this essay is to examine under what laboratory conditions rate of return parity is observed. The general findings of this investigation are that rate of return parity is observed in simple laboratory environments. The degree to which rate of return parity is observed is reduced as the environment becomes more complex.

This is important as knowing under what conditions, if any, rate of return parity is observed in a laboratory setting can serve as a guide to when and if the assumption of rate of return parity should be applied in models of open economy macroeconomics.

The remainder of this paper is organized as follows. Section II will present the experimental design and laboratory environment in which rate of return parity will be tested, this section is presented before the closer examination of the theory in order to provide a frame of reference when discussing the theory. Section III presents a closer examination of the central theory behind rate of return parity, and will explain the specifics of how rate of return parity is to be observed in the experimental environment. Section IV presents the results of the laboratory experiments. Section V draws conclusions from the experiment.

II. Experimental Design and Laboratory Environment

This experiment consisted of five treatments run at the McMaster University Experimental Economics Laboratory. Fifteen sessions were run. Ten subjects recruited from the student population of McMaster University participated in each session. The subjects that participated in each session had not participated in any other session of this experiment. Payoffs to subjects ranged from $12.25 to $104.50, with a mean of $38.45 and a standard deviation of $21.19.

The laboratory environment will be explained in detail in the following sections. The key components of the environment are: the markets, the behaviour of the exchange rate that links the two currencies, the nature of the assets, and the endowments of subjects. Each of these aspects as well as the overall experimental design will be discussed in turn below. The differences between the laboratory environment presented in this essay and that used by Fisher and Kelly [2000] will be discussed below.

A. The Markets

International capital markets are double auction markets. Therefore the asset markets in this experiment are double auction markets. A market for Blue Assets using Blue Dollars as the medium of exchange and a market for Red Assets using Red Dollars as a medium of exchange were conducted simultaneously. Each subject had the ability to act as a trader of assets in each of the two asset markets. The assets paid uncertain, but well-defined, dividends at the end of each trading period. The specific dividend structures are explained in part C below. A copy of the screen used by subjects and the instructions can be seen in Appendix 2.1. Instructions were distributed to each subject and then read aloud at the beginning of each session. These instructions fully describe to subjects how to enter bids and asks, as well as how to accept an outstanding bid or ask. In Treatments 1 through 4 each session consisted of 20 three-minute trading periods.[3] The sessions of Treatment 5 consisted of 16 three-minute periods. At the beginning of every session each subject received an endowment of equal expected value, based on the expected exchange rate and the expected dividends and trading at the assets' fundamental values. Endowments consisted of some combination of Red Assets, Blue Assets, Red Dollars ($R), and Blue Dollars ($B). The specific endowments used are presented in part D. Having received their initial endowments subjects' inventories of currency and assets were carried over from period to period. This meant that the supply of assets was held constant while the supply of currencies was increased each period by the amount paid to traders as dividends. At the end of each session subjects' holdings of Blue Dollars were converted into Red Dollars at the exchange rate of the last period. Subjects' holdings of Red Dollars were then converted into Canadian Dollars ($C) at a previously announced conversion rate.[4]

B. Exchange Rate Behaviour

In the first four treatments the exchange rate was fixed at 1 Red Dollar for 1 Blue Dollar. This creates an environment very similar to that used by Fisher and Kelly [2000]. The existence of separate currencies can be thought of as a framing feature when subjects knew the exchange rate was perfectly fixed. Subjects were informed that there was no possibility of the exchange rate changing in these treatments. In the fifth treatment the exchange rate was initially set at 8 Red Dollars for 1 Blue Dollar. In this treatment there was the possibility that

[3] Session 3 ran for 18 period and session 4 ran for 19 periods due to problems with the computer network.

[4] $C1 = $R66 in Treatment 1 and 2, $C1 = $R77 in Treatment 3 and 4, $C1 = $R200 in Treatment 5 .

the exchange rate would be devalued after each trading period. The devaluation of the exchange rate occurred with a constant probability of 0.25 (1 chance in 4). If the exchange rate was devalued in one period this did not have an impact on the probability of a devaluation after the next period. The actual devaluation of the Blue currency that would occur, if there was a devaluation, was always fifty percent (One Blue Dollar would buy half as many Red Dollars). The sessions of Treatment 5 were shorter to limit the number of potential devaluations.

C. The Nature of the Assets

The majority of Fisher's and Kelly's [2000] treatments dealt with assets which had four possible dividends. The same is true of the work of Smith, Suchanek, and Williams (1988).[5] The experiment presented in this chapter is intended to be as simple as possible while allowing sufficient opportunity for alternate models of behaviour. Accordingly assets in each period of each session in this experiment could pay either a high or a low dividend. The likelihood of the high dividend was fifty percent in all treatments.

In the first treatment both the Red and Blue Assets had the same high and low dividends. This treatment will give rate of return parity the greatest likelihood to hold. For the second treatment the dividends of both the Red and Blue Assets had the same expected value, but the possible dividend of the Blue Asset had a higher variance. This treatment will test the impact of asset specific risk on rate of return parity. In the third treatment the expected

[5] When asked about the choice of 4 possible dividends as opposed to another number of potential dividends Vernon Smith responded, "No reason–4 is good round number. The software accommodates up to a six point distribution as I recall." Personal Correspondence October 11, 2000.

dividend paid to holders of both assets had the same variance but the Blue Asset had a higher expected dividend than the Red Asset. This treatment allows the examination of assets of different expected dividends on rate of return parity. In the fourth treatment the expected dividend of the Blue Asset was higher than that of the Red Asset, but the dividend of the Blue Asset also had a higher variance. This treatment allows the consideration of the impact of very dissimilar assets on rate of return parity. The fifth treatment was designed to test the robustness of rate of return parity in a relatively complex environment. The complexity of the environment is driven by the possibility of a change in the exchange rate between trading periods. The sets of possible dividends used in each treatment can be seen in Table 2.1.

In Table 2.1, D_i indicates the possible dividends for the Red and Blue Assets in terms of Red and Blue Dollars, as the subscript indicates. The E, represents the standard expectations operator. The dividends and difference in variance reported in Table 2.1 are in terms of the Red or Blue currency respectively. From the expected dividend values the risk neutral expected dividend price can be calculated. The specific calculations are discussed in the Section IV below.

In each of the five treatments the dividends of the Red and Blue Assets were independent. In all treatments the dividend values were determined by the rolls of coloured dice. A red die was rolled to determine the dividend of the Red Asset and a blue die was rolled to determine the dividend of the Blue Asset. The rolls and respective dividends were recorded on a chalk board at the front of the laboratory in appropriately coloured chalk.

D. Endowments

In each treatment there were two different endowment groups. One endowment group received more Red Dollars than Blue Dollars and received more Blue Assets than Red Assets. The other received more Blue Dollars than Red Dollars and received more Red Assets than Blue Assets. This was done to encourage subjects to participate in both asset markets. The specific endowments are shown in Table 2.2. In all treatments, endowments have the same expected values if subjects did not trade or exchange currency.

E. Overall Design

The overall design of the experiment can be referred to as semi-factorial. Two treatment variables, namely expected dividends on assets and the variance of expected dividends, are fully interacted. This is the fully factorial aspect of the design. The "semi" portion of the design arises out of Treatment 5. The design table is presented in Table 2.3.

III. Predictions of Theory

Uncovered interest rate parity, described by Equation (2.1) is central to many economic theories. It is a condition derived from the assumption that trades by expected value maximizing risk-neutral traders will eliminate any differences in the expected value of alternative investments. Typically, uncovered interest rate parity focuses on specific assets, with little or no opportunity for capital gains from holding such assets. Modifying uncovered interest rate parity to include the possibility of capital gains leads to rate of return parity, described by Equation (2.2) below.

$$E(y_1) + E(g_1) = E(y_2) + E(g_2) \tag{2.2}$$

Where y_i is yield on asset 1 or asset 2 measured in percentage, g_i is capital gain from holding asset 1 or asset 2 again measured in percentage, and E is the standard expectations operator. Rearranging Equation (2.2) leads to Equation (2.3)

$$E(y_1) - E(y_2) = E(g_2) - E(g_1) \tag{2.3}$$

If rate of return parity between two assets is to be observed, the difference in the expected yields of the assets must be equal to the difference in expected capital gains. Thus, rate of return parity places no restrictions on yields unless the capital gains are known.

When considering rate of return parity in the experimental environment described in Section II, one should note that there are not simply two assets, but four available to agents. The Red and Blue currencies along with the Red and Blue Assets are all assets from the perspective of the agents participating in the experiment. Rate of return parity can be applied to any pairing of assets. There have been a number of experiments that have tested rate of return parity between a single asset and a currency. Most notable among these is Smith, Suchanek and Williams [1988]. Applying Equation (2.3) to an environment with a single asset and a single currency is actually quite simple. If asset 1 is the laboratory currency and asset 2 is the laboratory asset with uncertain dividends Equation (2.3) becomes;

$$E(y_{currency}) - E(y_{asset}) = E(g_{asset}) - E(g_{currency}) \tag{2.4}$$

For all agents in this type of experiment, holding the laboratory currency means receiving no dividends with certainty, and therefore, the yield on the currency is 0. Further the conversion rate between the laboratory currency and the payment medium of subjects is constant, thus, the capital gain to holding currency is simply 0. In this type of experiment the price of the asset with uncertain dividends at the end of the session is 0. Therefore if agents have time horizons that extend to the end of the session the expected capital gain will be;

$$E(g_{asset}) = \frac{0 - P_{asset,t}}{P_{asset,t}} = -1 \tag{2.5}$$

Where $P_{asset,t}$ is the current price of the asset with uncertain dividends. From Equation (2.5) it is clear that the expected capital gain to holding an asset will be negative 100% of the price paid for the asset. If there are N periods remaining in the session, the expected yield on the asset with uncertain dividends will be;

$$E(y_{asset,t}) = N \cdot \frac{E(D_{asset})}{P_{asset,t}} \tag{2.6}$$

Where D_{asset} is the dividend paid to holders of the asset at the end of each period. Applying these arguments to Equation (2.4) demonstrates that rate of return parity between a laboratory asset with uncertain dividends and a laboratory currency requires;

$$P_{asset,t} = N \cdot E(D_{Asset}) \tag{2.7}$$

In Smith, Suchanek, and Williams [1988], Fisher and Kelly [2000], and other works rate of return parity between a laboratory currency and an asset with uncertain dividends has not been observed. This observation of previous research leads to prediction 1.

Prediction 1: Rate of return parity between laboratory currencies and assets with uncertain dividends will not be observed. More specifically, in all treatments rate of return parity between Blue Dollars and Blue Assets will not be observed, nor will rate of return parity between Red Dollars and Red Assets.

Prediction 1 is equivalent to saying that price bubbles will be observed in both asset markets. This prediction is supported by Fisher and Kelly [2000]. It should be noted at this time, that this failure to observe this formulation of rate of return parity may be driven by agents who do not have time horizons that extend to the end of the session. The behaviour of agents in this environment may be consistent with a myopic rate of return parity principle in which the agents consider only the returns for the coming period. In such a scenario any yield on the asset with uncertain dividends is consistent with some expected capital gain. Thus the myopic rate of return parity principle cannot be refuted unless expectations of capital gains can be observed.

Fisher and Kelly [2000] have investigated laboratory environments in which there are two assets with uncertain dividends. In this environment Fisher and Kelly find that the prices of the assets with uncertain dividends are correlated. However, the results of the laboratory environment employed by Fisher and Kelly are inconsistent with full rate of return parity for agents with time horizons that extend to the end of the session. In all sessions in which the markets were populated by only inexperienced traders, price bubbles were observed. This is the support for prediction 1 as cited above. Again, this result is consistent with the findings from experiments in which agents traded a single asset with uncertain dividends.

Suppose, however, that agents equate the expected rate of return from the assets with uncertain dividends *without considering the alternative strategy of holding currency.* Rate of return parity then requires;

$$E(y_{blue}) - E(y_{red}) = E(g_{red}) - E(g_{blue}) \qquad (2.8)$$

If agents have time horizons that extend to the end of the session, $E(g_{red}) = E(g_{blue}) = -1$, as was shown in Equation (2.5). Therefore rate of return parity requires the yield on the Blue Asset will be equal to the yield on the Red Asset, if agents do not consider the alternate strategy of holding currency.[6] Therefore,

$$E(y_{blue}) - E(y_{red}) = 0 \;\Rightarrow\; E(y_{blue}) = E(y_{red}) \qquad (2.9)$$

Applying Equation (2.6) to Equation (2.9) forms Equation (2.10).

$$P_{blue} = P_{red} \cdot \frac{E(D_{blue,t})}{E(D_{red,t})} \qquad (2.10)$$

Equation (2.10) is the basis of prediction 2.

Prediction 2: Under risk neutrality the price of the Blue Asset will be equal to the price of the Red Asset multiplied by the ratio of expected dividends for all treatments.

Both predictions 1 and 2, have assumed that agents are risk neutral. This may not be true of the agents that populate the laboratory environment. If agents are risk averse, or risk preferring then Equation (2.2) does not capture the relationship between the assets in question. Many researchers attempting to find evidence of rate of return parity have posited that risk does in fact play a key roll in actions of traders. If such is the case, Equation (2.9) needs to be modified to include risk premia.

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[6] It should be noted that any behaviour that equates the expected capital gains of the two financial assets will lead to Equation (2.9)

$$E(y_{blue}) - E(y_{red}) = \Theta(\sigma_{red}) - \Theta(\sigma_{blue}) \qquad (2.11)$$

Where $\Theta(\sigma_i)$ is the risk premium on asset i.

If agents are risk averse the risk premium will be positive and increasing in the variance of dividends, thus the yield on the asset with the greater variance in the value expected dividends will be higher than the yield on the asset with the lower variance in the value of expected dividends. There is a difference in the variance of the value of expected dividends in Treatments 2, 4, and 5. In Treatments 2 and 4, the dividends of the Blue Asset have a greater variance than the dividends of the Red Asset. In Treatment 5 the difference in the variance of the value of expected dividends arrises due to the possibility of an exchange rate change. This leads to prediction 3.

Prediction 3: If agents are risk averse, $\Theta(\sigma_{blue})$ will be greater than $\Theta(\sigma_{red})$ when the variance in dividends of the blue asset is greater than the variance in dividends on the red asset. Therefore, the price of the Blue Asset will be less than the price of the Red Asset multiplied by the ratio of expected dividends in Treatments 2, 4, and 5.

Armed with these predictions we can examine the data generated in the laboratory environment.

IV. Empirical Results

The data generated by this experiment are time series data with all the inherent difficulties and subtleties. One of the major difficulties is matching data points within periods. Unless transactions occur at exactly the same moment in time there is no exact match in individual transaction prices. Researchers using field data have used a variety of data points, such as closing price on a specific date, at the end of the day, month or quarter. To overcome this problem while including as much of the data generated as possible the average transaction price in each period is used.[7] In those cases in which no transaction occurred in a given period the midpoint between the outstanding bid and ask was used as a proxy.

The analysis of the data is taken in two levels. First is a visual inspection of the average price data and the deviations of the price of the Blue Asset from the values predicted in Equation (2.10). Second is a consideration of descriptive statistics for each session and treatment as well as non-parametric and parametric tests.

A. Visual Inspection

Analysis of the data begins with a visual inspection of the price data. Figures 2.1 through 2.5 below show the average trade price in both the Red and Blue Asset markets in each for all sessions as well as the deviation of the Blue Asset price from the value predicted by Equation (2.10). In all but one session of Treatment 1 (Figure 2.1) asset prices exhibit obvious price bubbles. The price of both assets rises well above the value suggested by rate of return parity between currency and assets with uncertain dividends in early to middle periods, then falls to the value suggested by rate of return parity towards the end of the session. This is the same pattern observed by Smith, Suchanek, and Williams [1988] and Fisher and Kelly [2000]. These observations support prediction 1.

In spite of this deviation from rate of return parity between currency and assets with uncertain dividends the Red and Blue Asset prices appear to move together in all sessions with

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[7] Average transaction prices in each period are often used in analyses of experimental asset markets. See Sunder [1995].

the exception of one session of Treatment 5 (Figure 2.5). In Treatment 1, when assets had the same expected dividend and variance in dividends, the two price series are virtually indistinguishable. This is further supported by the graph of deviations of the Blue Asset price from its predicted value based on rate of return parity between assets with uncertain dividends. In Treatment 2, when assets had the same expected value but different variances in dividends, the Red Asset price is generally higher than the Blue Asset price, with the greatest difference being observed in Session 2.3. The deviations of the Blue Asset price from its predicted value still appear to be close to 0 in this treatment. In Treatment 3, when assets had the different expected dividends and the same variance in dividends, the Blue Asset price is generally higher than the Red Asset price, though the difference is smaller than expected on average, as is shown in the right hand panel. The data from Treatment 3 support prediction 1 but not prediction 2. In this treatment the variance in dividends is equal, thus prediction 3 is not relevant to this treatment. In Treatment 4, when assets differ in both expected dividend and variance of dividends, prices do appear to move together but less than in Treatments 1, 2, or 3. The price of the Blue Asset is generally higher than that of the Red Asset as is predicted by theory. The data plots of Treatment 5, when the exchange rate was subject to random changes, show that there is a fair degree of similarity in the price movements in Sessions 5.1 and 5.3. There does appear to be little co-movement of the two price series in Session 5.2. In terms of visual analysis, some support can be found for predictions 1 and 2. The vast majority of sessions exhibit price bubbles. The price series in Treatment 1 do appear very similar to the naked eye, thus some support can be lent to prediction 2. In Treatment 2, the price of the Blue Asset does seem to be below that of the Red Asset and offers some support for prediction 3 over prediction 2 . The difference in average asset prices can be taken as an indication that subjects are risk averse in this treatment. The data from Treatment 4 tells a slightly different story, however. Prediction 1 is supported, as prices bubbles are apparent. Prediction 2 is more difficult to assess in this treatment. The support for prediction 3 is limited by visual analysis of the data from Treatment 4, the difference in asset dividends in this treatment does not induce a price that is consistently lower than predicted by risk neutrality of subjects. In Treatment 5, it appears that when there is a difference in asset prices, the price of the Blue Asset is lower than the price in the Red Asset. This can be taken as visual confirmation of prediction 3.

B. Descriptive Statistics and Testing

The visual examination of the data is very helpful, but cumbersome. Before the degree to which rate of return parity holds can be discussed in more detail, the value of expected dividends must be discussed. The value of expected dividends paid to those agents that hold the Blue Asset is calculated as

$$E(\sum D_{blue}) = \frac{e_t E(D_{blue}) r \left(1 - r^{T-t+1}\right)}{(1-r)} \tag{2.12}$$

Where e_t is the exchange rate at the start of period t expressed as Red Dollars per Blue Dollar, r = 1 - (1-k)p, T is the number of periods in the session, t is the current period. In the r term, k is the proportion by which the exchange rate between Red Dollars and Blue Dollars is devalued and p is the probability of a devaluation at the end of a trading period. In Treatments 1, 2, 3, and 4, the values of k and p are exactly zero, thus the value of expected dividends paid to those that hold Blue Assets in these treatments can be calculated in exactly the same manner as the value of expected dividends paid to those that hold Red Assets as seen below. In Treatment 5 the value of k is 0.5 and the value of p is 0.25. This value must then be converted back into Blue Dollars so that the price of the asset in the markets may be compared to its predicted value. The conversion from Equation (2.12) above is done by dividing by the value of e_t. This converted value is the value that will be used when considering the veracity of prediction 2.

The value of expected dividends paid to those agents that hold the Red Asset is simply;

$$E(\sum_{t}^{T} D_{red}) = (T - t) \cdot E(D_{red}) \qquad (2.13)$$

Predictions 2 and 3 are concerned with the relative prices of the assets with uncertain dividends. Prediction 2 states that risk neutral rate of return parity will exist between the assets with uncertain dividends. Prediction 3 states that the price of the Blue Asset will be lower than the price of the Red Asset in Treatments 2, 4, and 5 if agents are risk averse. These predictions are not necessarily dependent on rate of return parity being observed between assets with uncertain dividends and currency. It was assumed in Section III that agents might ignore the possibility of holding currency and focus on holding assets. There are two issues of interest to predictions 2 and 3 presented Section III. The first issue is the bias of prediction errors. If the median and/or mean prediction error from rate of return parity is consistently in the same direction this is evidence that subjects had a bias toward one or the other of the assets. Under the prediction 2, risk neutral rate of return parity, there should be no bias, and the differences would be determined by a random error process centred around 0. Under prediction 3, risk aversion, one would expect a bias in the price differences in Treatments 2, 4, and 5.

Table 2.4 shows the median, mean, and standard deviation of the difference between the actual Blue Asset price and the rate of return parity predicted Blue Asset price in each session.

To this end consider the median and mean deviation of Blue Asset prices from the rate of return parity predicted value. Treatment 1 shows no consistent bias. The medians of the 3 sessions are of different sign or zero. This is a strong indication that there is no bias in relative asset prices in this treatment. This result neither confirms nor refutes risk neutrality, as the variance of expected dividends of both the Red and Blue Assets are identical. Consider now the prediction errors in Treatment 2. In this treatment, the median and mean prediction errors are negative, indicating that the Blue Asset price was on average below its risk neutral predicted value, thus there is a bias against the Blue Asset. This fact offers some support for risk averse behaviour on the part of subjects and therefore prediction 3. It is also interesting to note that this result is not carried through to Treatment 4 in which the assets differed in both expected dividend and variance of expected dividend, thus Treatment 4 offers support for prediction 2 over prediction 3. Treatment 3 also exhibits negative average deviations of the Blue Asset price from its predicted value. This cannot be seen as evidence of risk averse behaviour, but a bias in asset pricing by subjects. The subjects in these sessions on average underpriced the Blue Asset. This is an indication that subjects were unable to fully exploit arbitrage opportunities when there were differences in expected dividends, in spite of identical variances. This consistent negative average prediction error does not characterize in Treatment 4. The median and mean price deviations in treatment 4 are not a simple combination of the deviations in Treatments 2 and 3 in terms of sign, but something entirely different. This can be viewed as evidence that subjects are unable to deal with complex differences in underlying fundamental asset values in, and thus refutes both predictions 2 and 3. It appears that the previously observed bias is undone by the complex difference in the fundamental nature of the assets. Treatment 5 also provides some insight into the behaviour of subjects in relatively complex environments. The bias of relative asset prices is inconsistent in this treatment and the average bias is rather small, though the standard deviation of bias is large in comparison to other treatments. The second issue concerning prediction 2 is the size of the prediction errors. Smaller prediction errors indicate that the level of arbitrage is high and rate of return parity is a strong predictor of relative asset prices. The greater the size of the prediction error the lower the level of arbitrage and subsequent predictive power of rate of return parity. The degree of arbitrage or the overall predictive power of the rate of return parity relationship can be considered via the median, mean, and standard deviation of the absolute values of deviations from rate of return parity. The smaller the prediction error the greater the accuracy of Equation (2.10). Data on this issue is presented in Table 2.5. Table 2.5 below shows the median, mean, and standard deviation of the absolute difference between Blue Asset prices from the rate of return predicted value in each session.

In Treatment 1 the predictions errors are smaller in absolute value than in any other treatment. This can be seen as an indication that rate of return is a better predictor of the Blue Asset price when the Blue and Red Assets are identical. Consider Treatment 2. The magnitude of the median and mean prediction errors are smaller than in most of the remaining treatments, this can be seen as an indication that differences in dividend variance have a limited impact on the degree of arbitrage. In general the magnitude of prediction errors in treatment 3 is larger than in the previous two treatments, this is evidence that difference in fundamental asset values reduces the level of arbitrage and thereby the predictive power of rate of return parity. As the Assets become more and more different the median and mean prediction error of the Blue Asset price becomes greater. The magnitude of the prediction errors is generally increased, indicated that arbitrage further breaks down in the face of complex differences assets, this is true of treatment 4. The largest average prediction error is observed in Treatment 5. The remaining 2 median and mean prediction errors. This would seem to indicate that exchange rate risk does in fact pose a problem for subjects in terms achieving high levels of arbitrage.

In all the simple inspection of medians, means, and standard errors offers support for prediction 2 in Treatments 1 and 2. The increase in absolute prediction errors in later treatments indicates that the degree of support for rate of return parity between assets with uncertain dividends is reduced as the environment becomes increasingly complex. The exceptionally high absolute deviations from rate of return parity in Treatment 5 are an indication that rate of return parity is not observed in these sessions.

In order to apply formal methods of analysis to this data, the treatment means of bias and tightness of arbitrage need to be considered. Tables 2.6 and 2.7 presents the treatment averages for bias measures while Tables 2.8 and 2.9 present the treatment averages for tightness of arbitrage measures.

The data presented in Tables 2.6 and 2.7 are analysed using a Kruskal-Wallis test on session medians and a regression of mean prediction error on treatments using the Huber/White/sandwich estimation of variance. As there is no reason to assume that the data in question has any specific distribution, non-parametric testing is the ideal manner in which to proceed. Kruskal-Wallis tests support the suspicion that there is no significant difference in the bias of rate of return parity prediction errors by treatment. The Kruskal-Wallis test returns an H-statistic of 5.7 with a p-value of 0.2227. The null hypothesis of no difference in treatment means cannot be rejected by on the results of this test. The Kruskal-Wallis test is of low power with small sample sizes, however. Thus it is unclear whether the failure to reject the null hypothesis of no treatment effects is due the small sample size or that there are in fact no treatment effects.

In light of the uncertainty as to why the Kruskal-Wallis test lead to the failure to reject the null hypothesis of no treatment effects parametric testing becomes more appealing. Analysis of variance (ANOVA) is quite similar to the Kruskal-Wallis test in terms of the null hypothesis. ANOVA requires that assumptions must be made regarding the nature of variance of the data in question, specifically, that the data is homoskedastic. Visually inspecting the data in Table 2.4 it appear that there is heteroskedasticity. This observation is further supported by the Cook-Weisberg test for heteroskedasticity, which returns a chi^2 of 21.94 with 4 degrees of freedom and an associated p-value of 0.0002. The results of the Cook-Weisberg test strongly reject the constant variance as a function of treatment. Thus the data violate one of the basic assumptions of ANOVA testing and an alternate method of examining the data is in order.

The alternate method employed to address the issue of heteroskedasticity is to estimate the treatment means using regression techniques while applying the Huber/White/sandwich robust estimation of parameter variance. This is done by regressing the mean prediction error by treatment, as reported in Table 2.4, on 5 dummy variables - one for each treatment. Thus the parameter estimates from the regression will be robust estimates of the treatment mean prediction error with appropriate variance. The results of this procedure are reported in Table 2.8.

The results shown in Table 2.8 need to be interpreted with care. The p-values shown in the table do not correspond with the null hypothesis of the Kruskal-Wallis test presented above. The null hypothesis of the Kruskal-Wallis test is that there is no difference in the bias of median prediction errors from rate of return parity between treatments. The null hypothesis being tested is that the coefficient on each treatment dummy is equal to zero. Based on the results shown in Table 2.8 one would fail to reject this null hypothesis for Treatments 1, 4, and 5. In Treatments 2 and 3, however, the null hypothesis of zero bias is rejected. This rejection of the null hypothesis only suggests that if repeated sampling were conducted (additional sessions of the experiment) and means calculated in the same manner, the means would not equal zero in 1 minus the p-value proportion of samples. Given the fact that one cannot reject the null hypothesis of zero bias in Treatment 1 and the apparently small estimated standard deviation, the results shown in Table 2.8 provide a high degree of support for rate of return parity in Treatment 1. The support for the remaining treatments is much lower. In Treatment 2 and Treatment 3 zero bias is rejected, thus the data do not appear to support rate of return parity in these treatments. The failure to reject zero bias in Treatment 4 and Treatment 5 should not immediately be taken as support for rate of return parity in thus treatments. The estimated standard errors should to test the null hypothesis are significantly larger than in the other three treatments. Further analysis will be required before any conclusions can be drawn concerning rate of return parity in Treatment 4 and Treatment 5.

From the estimates of treatment means presented in Table 2.8, a pair-wise comparison can be conducted. This process is still not identical to the null hypothesis of the Kruskal-Wallis test, but it is closer than comparing the estimates to zero. The results of this procedure are shown in Table 2.9

Based on this pair-wise testing one can only reject the null hypothesis of equal treatment means for comparisons between Treatment 1 and Treatment 2, as well as Treatment 1 and Treatment 3. In all remaining comparisons the null hypothesis of no difference in treatment means cannot be rejected. Thus there is some difference in the bias of the prediction errors of rate of return parity between treatments. The finding that the bias in Treatment 2 is significantly different from Treatment 1 offers some support for Prediction 3. The difference in bias could potentially be seen as an indication that the risk associated with the asset mattered for the bias of rate of return parity. This supported is weakened by the finding that the bias of Treatment 3 is significantly different from that of Treatment 1 as well. In Treatment 3 there is no difference in the degree of risk associated with the assets, thus risk attitudes cannot be contributing to the difference in bias between Treatment 1 and Treatment 3.

The bias of the prediction errors is not the only issue in considering the applicability of rate of return parity to this experimental environment. The absolute magnitude of prediction errors is also important. Table 2.10 shows the mean absolute prediction errors by treatment, and Table 2.11 shows the average median prediction error by treatment.

A cursory visual inspection of the data shown in Tables 2.10 and 2.11 appears to indicated that there may well be a significant difference in the tightness of arbitrage between treatments. An unstable exchange rate (Treatment 5) stands out as having an mean absolute prediction error approximately three times that of other treatments. Any conclusions about significant differences must be made after the application of formal testing.

The first step in formally analysing the data presented in Table 2.8 and 2.9 is to apply a Kruskal-Wallis test of session medians. This test will indicate if there is a significant difference in the tightness of arbitrage between treatments. The Kruskal-Wallis yields an H-statistic of 12.7 with a p-value of 0.0128. Again one might be concerned with the low power of the Kruskal-Wallis test. This testing indicates that there is a significant difference in the tightness of arbitrage between treatments. The power of the test is not at issue in this case as the null hypothesis of no treatment effects is soundly rejected.

The most obvious partition of the data is treatments with stable exchange rates on one side and those with unstable exchange rates on the other. If the differences between treatments with stable and unstable exchange rates is the only difference between treatments driving the results of the Kruskal-Wallis test, there will be no significant difference between treatments with stable exchange rates. To this end, Kruskal-Wallis testing procedures are applied only to the sessions in which the exchange rate was fixed with certainty. The Kruskal-Wallis test returns an H-statistic of 9.667 with a p-value of 0.0216. Thus, there is a significant difference in the tightness of arbitrage between treatments even when the exchange rate is perfectly fixed. Again, as the null hypothesis is reject the low power of the test cannot be at issue. Therefore, instability of the exchange rate cannot be the sole source of difference in the tightness of arbitrage.

This finding does not negate the idea that unstable exchange rates and stable exchange rates is a meaningful partition of the data. There may still be a significant difference in the tightness of arbitrage between these conditions. A Mann-Whitney test of session median prediction errors returns a Z-statistic of -2.454 with a p-value of 0.0141. This result make it clear that there is a significant difference in the tightness of arbitrage between treatments in which the exchange rate is stable and those in which it is not. Exchange rate stability, however, cannot be the sole cause of differences in the degree of arbitrage in the data, as was stated above.

Given that there is a significant difference in the tightness of arbitrage between treatments in which the exchange rate is perfectly fixed, the impact of each treatment variable must be considered. This will require further partitions of the data. In keeping with the spirit of prediction 3, the data from sessions in which the exchange rate was perfectly fixed will be dividend into 2 groups. One group will consist of sessions in which the variance of asset dividends is identical (Treatments 1 and 3) and the second will be sessions in which the variance of asset dividends was different (Treatments 2 and 4). A Mann-Whitney test returns a Z-statistic of -0.48 with a p-value of 0.631. Testing fails to reject the null hypothesis of no difference between sides of the partition. This result appears contrary to the finding of research using field data [Fama 1984, Mayfield and Murphy 1992]. The failure to observe rate of return parity in the field (specifically uncovered interest rate parity) has be attributed to risk aversion and differences in the risk associated with assets. The analysis of the laboratory data do not support this.

Another possible partition of the data is session in which assets had identical expected dividends (Treatments 1 and 2) and sessions in which the expected dividends were different

(Treatments 3 and 4). A Mann-Whitney test returns a Z-statistic of -2.882 with a p-value of 0.0039. Under this partition testing strongly rejects the null hypothesis of no difference in the tightness of arbitrage between treatments. These results provide evidence that similarity in the nature of assets beyond the degree of risk are important in determining the degree of arbitrage.

Given that there is a significant difference the tightness of arbitrage when assets have different expected dividends, is there a difference in the tightness of arbitrage between treatments in which the assets have identical expected dividends but different risk? This amounts to a comparison between Treatments 1 and 2. A Mann-Whitney test returns a Z-statistic of -1.964 with a p-value of 0.0495. The analysis indicates that a difference in the variance of asset dividends does in fact matter when the assets have identical expected dividends.

Overall, the analyses indicates that rate of return parity is not observed between assets with uncertain dividends and currency, thus prediction 1 is rejected. It appears that rate of return parity between assets with uncertain dividends is observed in treatments in which the nature of the assets is very similar, namely Treatment 1. Rate of return parity between assets with uncertain dividends begins to break down as the assets become increasing different, namely Treatments 2, 3 and 4. The introduction of exchange rate uncertainty in Treatment 5, further weakens rate of return parity between assets with uncertain dividends. Thus prediction 2 is supported in Treatments 1, but receives little support in Treatments 2, 3, 4, and 5. The lack of a consistent difference in bias between those treatments in which there was a difference in the risks associated with different assets with uncertain dividends, namely Treatments 2, 4, and 5, indicates that the data do not support prediction 3. None of the data or analysis presented in this section is able to refute the possibility of rate of return parity if agents do no believe that the expected capital gains on assets are equal. Thus these data are limited to the consideration of rate of return parity in which capital gains on assets are assumed to be identical.[8]

V. Conclusions

The goal of this experiment was to test rate of return parity and the completeness of arbitrage across asset markets in increasingly complex environments while maintaining experimental control. In the first four treatments the exchange rate was fixed with complete certainty, thereby limiting the potential confounding factors in the rate of return parity relationship to the nature of the assets themselves. The fifth treatment tests the robustness of the rate of return parity relationship in an environment in which the exchange rate was subject to a degree of risk. This treatment allows consideration of the possibility of exchange rate risk having a unique impact on the behaviour of asset markets.

The results of the experiment lead to five basic conclusions. First, rate of return parity between assets with uncertain dividends and currency is not supported. Essentially, bubbles and crashes in the prices of the Red and Blue Assets are observed. This conclusion corresponds

[8] Many researchers using field data to consider rate of return parity have hypothesizedthat rate of return parity is observed as a long run phenomena. The empirical hypothesis in this case is that rates of return on two assets will be co-integrated. This technique was applied to the data generated by this experiment. The results are not included here as they differed little from the analysis presented above and there are issues of the power of Dickey-Fuller tests with the length of time series generated. If sufficient data were available, one could regress each Blue Asset price series on the right hand side of Equation (2.10). The residuals from this regression could then be tested for stationarity using the Dickey-Fuller test. If the residuals are found to be stationary, Equation (2.10) is in fact a co-integrating relationship and rate of return parity would be supported as a long run phenomena.

with the findings of earlier research into markets for assets that have multi-period life spans [Smith, Suchanek, and Williams 1988, Fisher and Kelly 2000].

The basic general conclusion is that rate of return parity is an accurate predictor of relative asset prices when assets are identical and the exchange rate between currencies is perfectly fixed. The data from this treatment of the experiment (Treatment 1) supports this result through visual examination, parametric, and non-parametric testing. This finding matches the finding of Fisher and Kelly [2000].

The third basic conclusion is that rate of return parity is a reasonably accurate predictor of relative asset prices in cases when assets differ only in the degree of risk and the exchange rate is fixed with certainty. The accuracy of rate of return parity in was significantly reduced in this treatment, however. This result is consistent with much of the often hypothesized influence of risk on rate of return parity. Specifically, many researchers using field data to test rate of return parity have suggested that the failure of simple rate of return parity is driven by risk factors.

Fourth, the support for rate of return parity as a predictor of relative asset prices is reduced as assets in question become more different. The degree to which rate of return parity was observed in the experimental data is significantly reduced by assets that have different expected dividends, (Treatments 3 and 4).

The final basic conclusion is that the support for rate of return parity is significantly reduced by exchange rate risk. In sessions in which the exchange rate between currencies was subject to random devaluation (Treatment 5), the support for rate of return parity was by far the weakest. This supports many of the findings of field research.

From these basic conclusions, a more general conclusion can be drawn. The data from this experiment do not support rate of return parity as an everywhere and always condition. Further, it is not simply exchange rate risk that confounds rate of return parity but differences in the fundamental nature of assets as well. These conclusions are drawn from data in which there were no barriers to capital mobility, nor any motivation for an innate non-pecuniary preference of investors for one asset or another. Therefore, applying any form of rate of return parity in situations where assets are different or exchange rate risk is present would be ill advised.

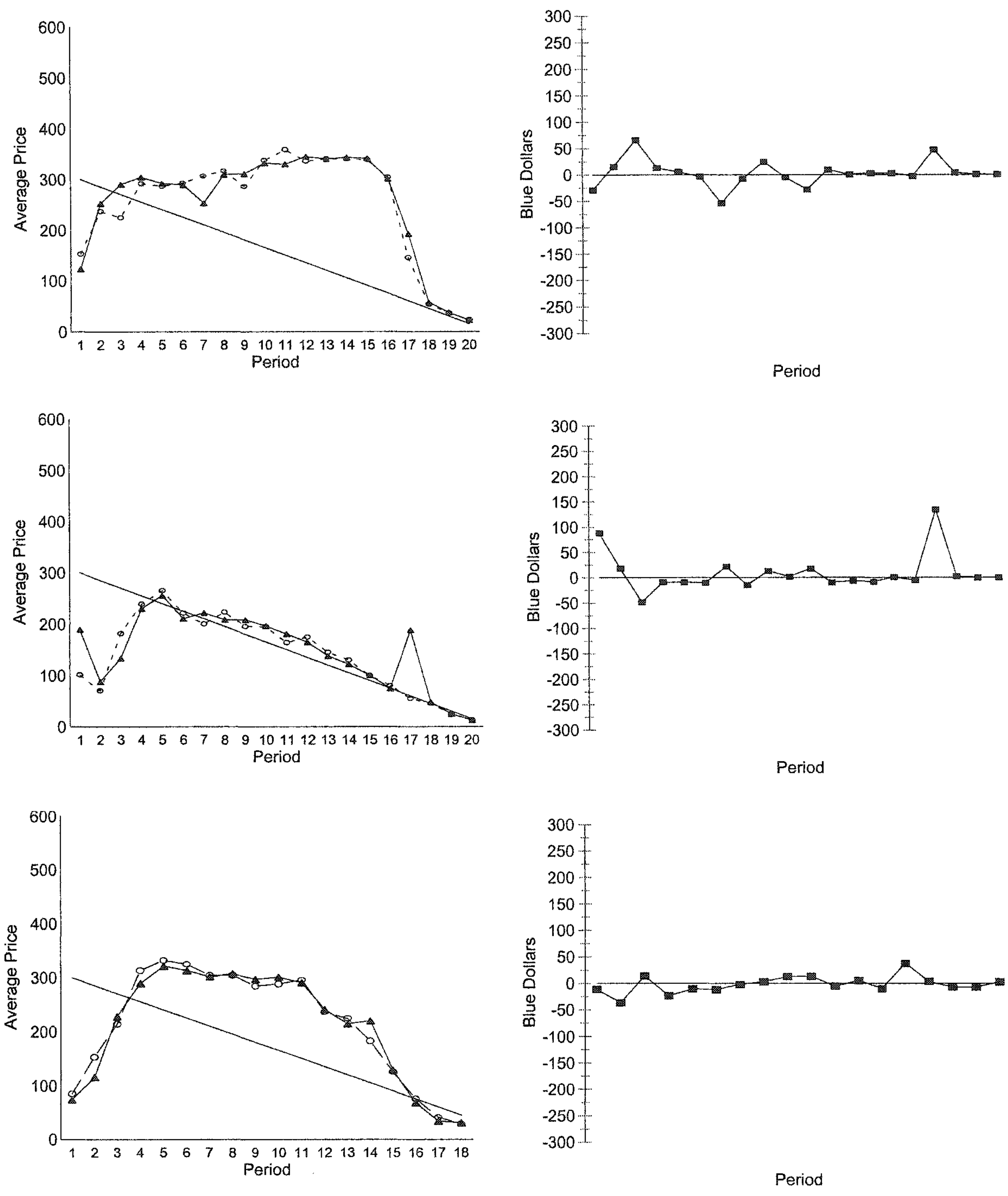


Fig. 2.1. Treatment 1, Sessions 1.1, 1.2 and 1.3 (Top to Bottom); Triangles are Blue Assets, Circles are Red Assets; Downward sloping lines in panels on the left identify fundamental asset values. Right-hand panels display differences between blue asset prices and the rate of return parity predicted value.

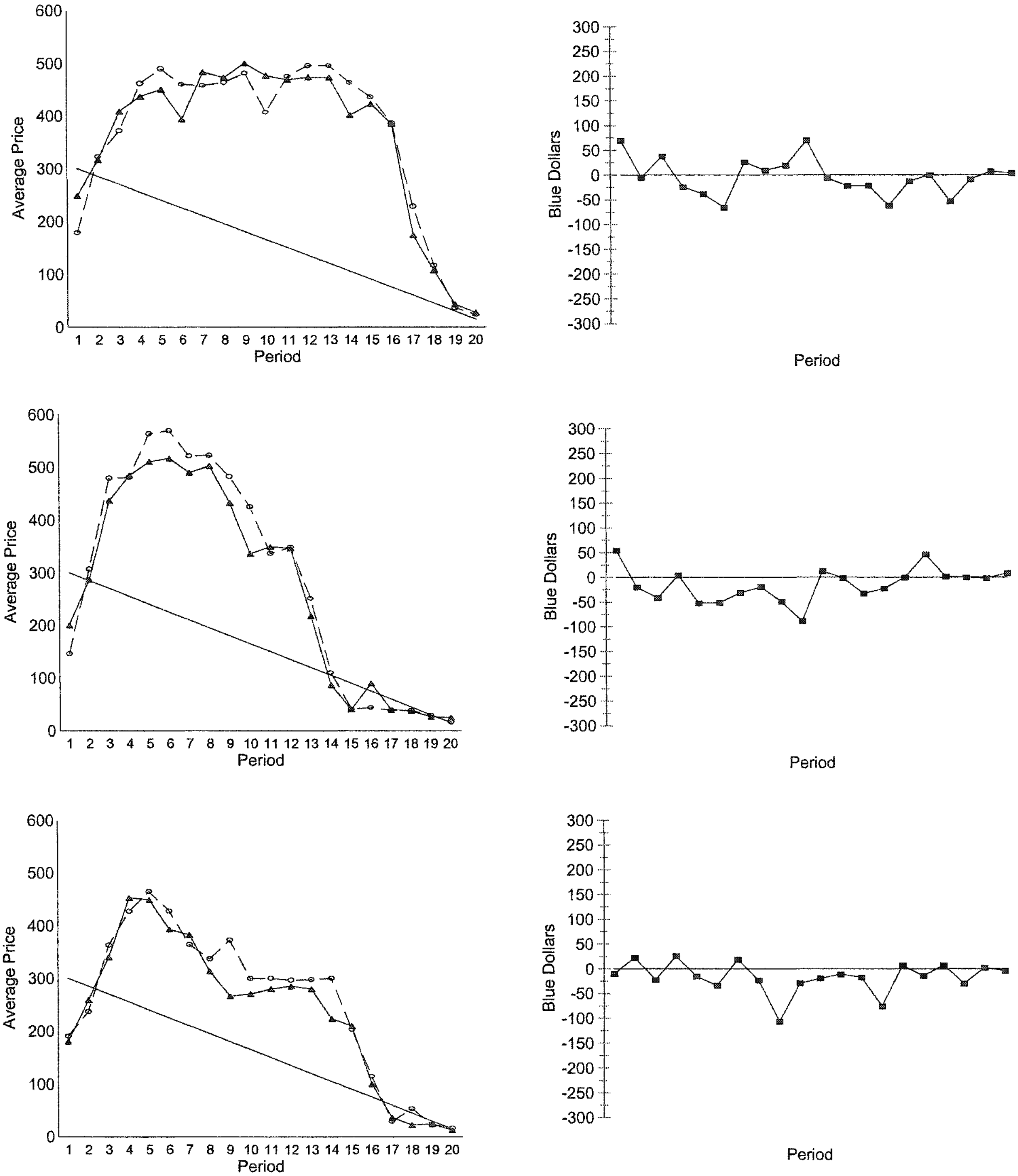


Fig 2.2. Treatment 2 Sessions 2.1, 2.2 and 2.3 (Top to Bottom); Triangles are Blue Assets, Circles are Red Assets; Downward sloping lines in panels on the left identify fundamental asset values. Right-hand panels display differences between blue asset prices and the rate of return parity predicted value.

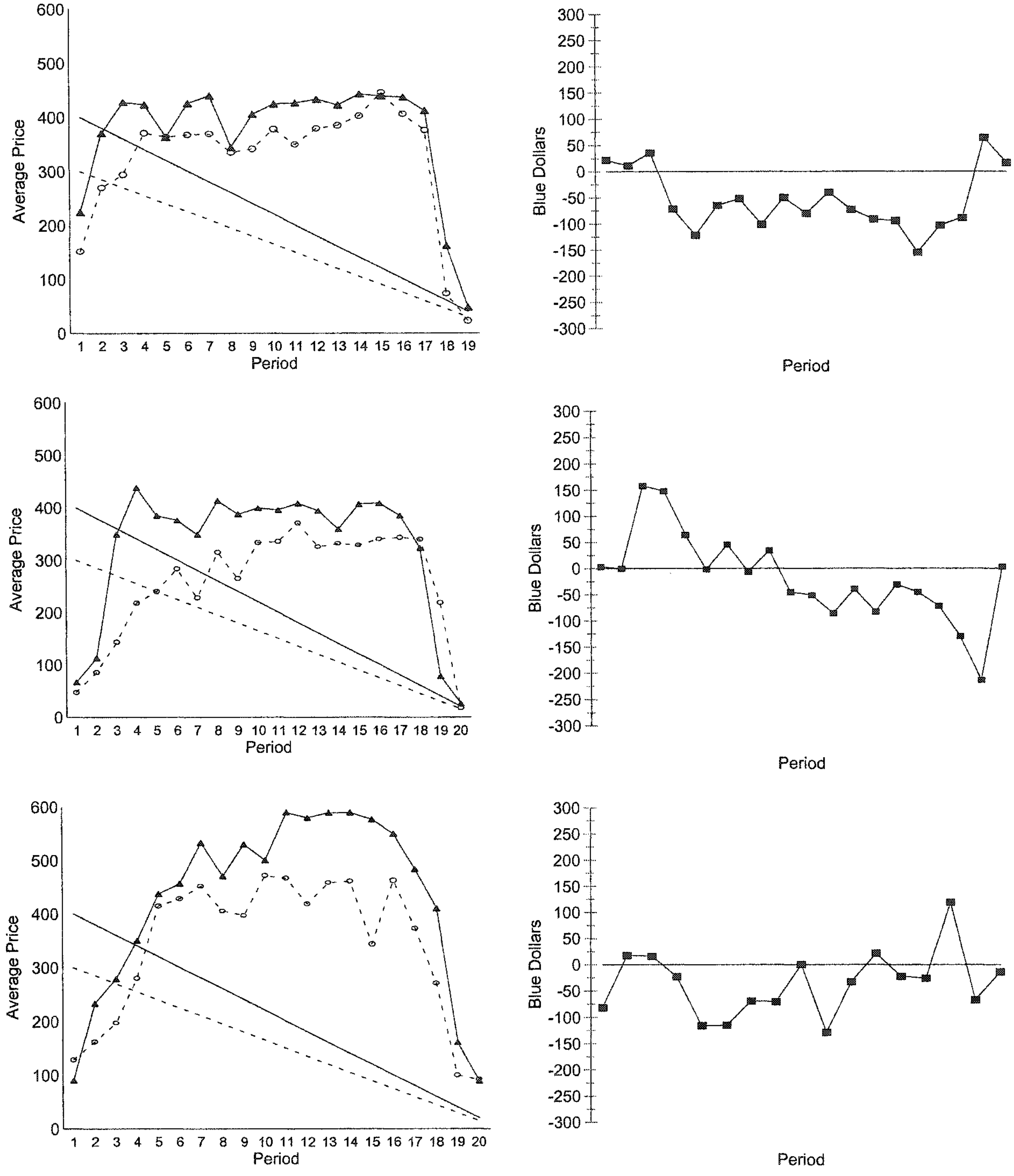


Fig. 2.3. Treatment 3, Sessions 3.1, 3.2 and 3.3 (Top to Bottom); Triangles are Blue Assets, Circles are Red Assets; Downward sloping lines in panels on the left identify fundamental asset values. Right-hand panels display differences between blue asset prices and the rate of return parity predicted value.

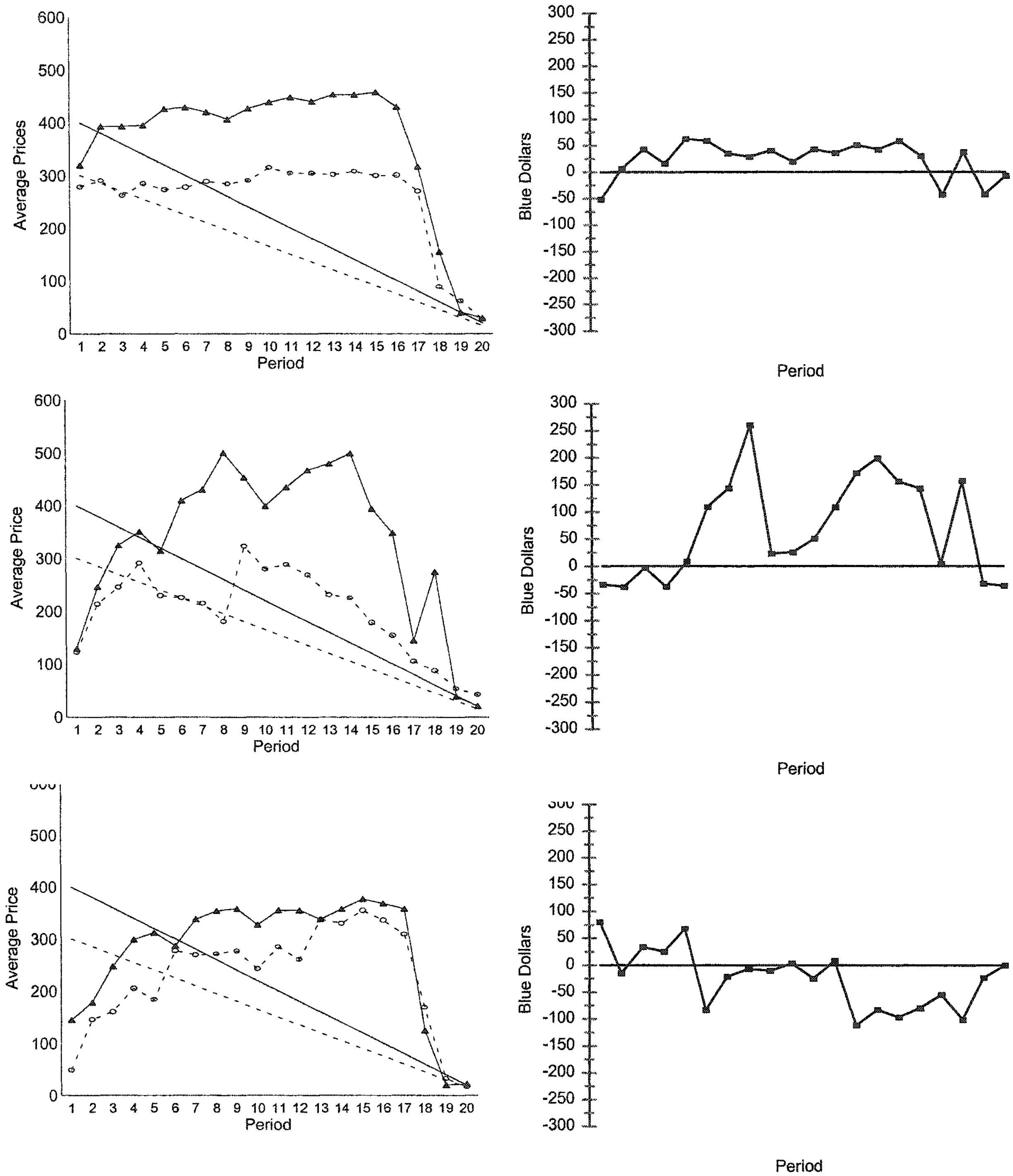


Fig. 2.4. Treatment 4, Sessions 4.1, 4.2 and 4.3 (Top to Bottom); Triangles are Blue Assets, Circles are Red Assets; Downward sloping lines in panels on the left identify fundamental asset values. Right-hand panels display differences between red asset prices and the rate of return parity predicted value.

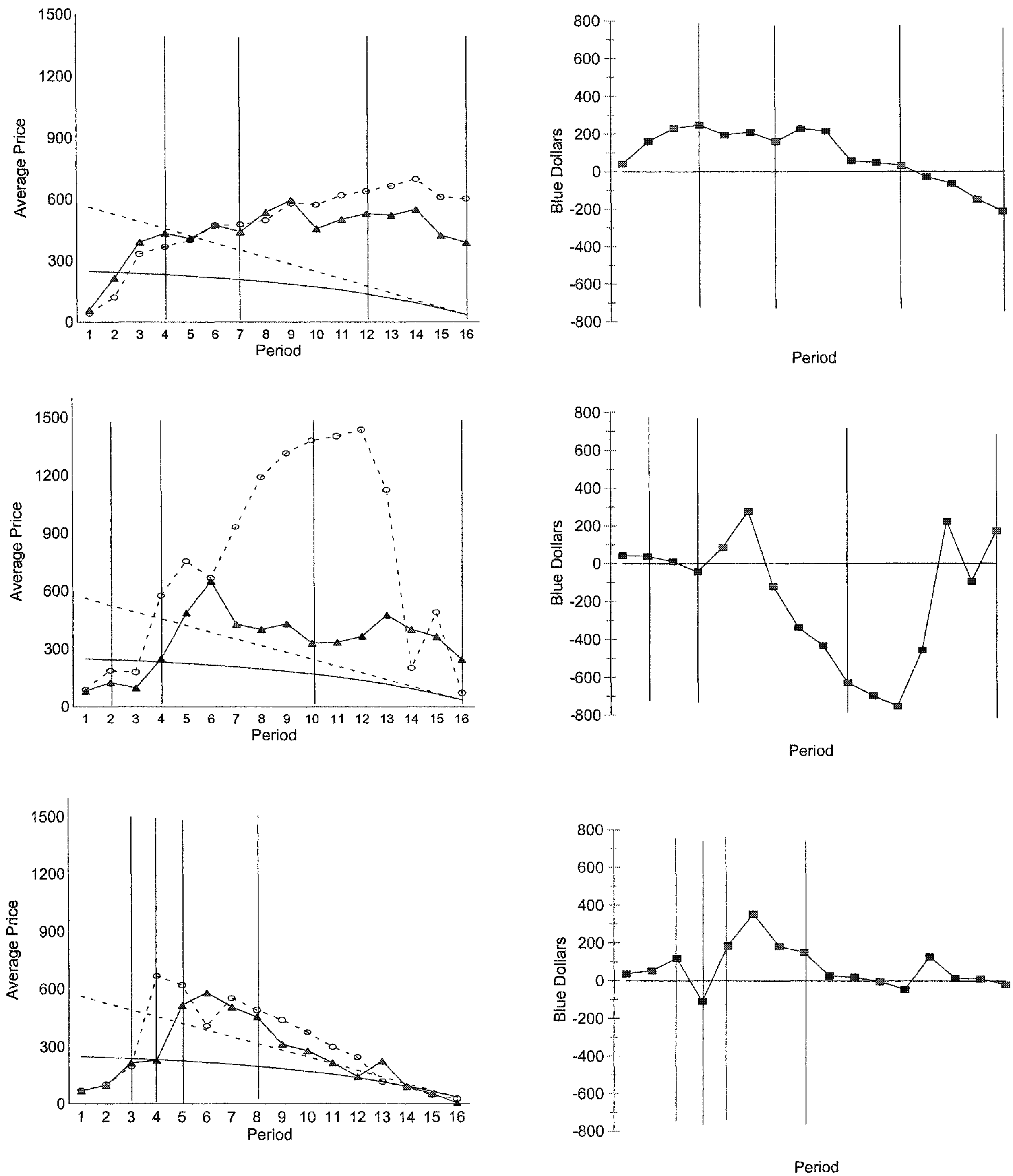


Fig. 2.5. Treatment 5, Sessions 5.1, 5.2 and 5.3 (Top to Bottom); Triangles are Blue Assets, Circles are Red Assets; Downward sloping lines in panels on the left identify fundamental asset values; Vertical lines indicate periods in which a devaluation occurred. Right-hand panels display differences between blue asset prices and the rate of return parity expected value.

Table 2.1 Asset Dividends

Treatment	Red Asset Dividend	Blue Asset Dividend	Difference in Variance
1	$D_R = (10,20)$: $E(D_R) = 15$	$D_B = (10,20)$: $E(D_B) = 15$	0
2	$D_R = (10,20)$: $E(D_R) = 15$	$D_B = (5,25)$: $E(D_B) = 15$	75
3	$D_R = (10,20)$: $E(D_R) = 15$	$D_B = (15,25)$: $E(D_B) = 20$	0
4	$D_R = (10,20)$: $E(D_R) = 15$	$D_B = (10,30)$: $E(D_B) = 20$	75
5	$D_R = (30,40)$: $E(D_R) = 35$	$D_B = (35,45)$: $E(D_B) = 40$	0, 70.3125*

* The difference in variance for Treatment 5 appears to be zero, but when potential changes in the exchange rate between currencies is taken into consideration, it can be shown to be 70.3125. This value approaches the difference in variance for Treatments 2 and 4.

Table 2.2 Endowments of Subjects

Treatment	Endowment	Red Dollars	Blue Dollars	Red Assets	Blue Assets
1	A	300	600	3	1
1	B	600	300	1	3
2	A	300	600	3	1
2	B	600	300	1	3
3	A	300	800	3	1
3	B	600	300	1	3
4	A	300	800	3	1
4	B	600	300	1	3
5	A	400	640	3	1
5	B	435	250	1	3

Table 2.3 Design Table

	Stable Exchange Rate		Unstable Exchange Rate	
	$E(D_B) = E(D_R)$	$E(D_B) > E(D_R)$	$E(D_B) = E(D_R)$	$E(D_B) > E(D_R)$
$var(D_B) = var(D_R)$	3 observations	3 observations	0 observations	0 observations
$var(D_B) > var(D_R)$	3 observations	3 observations	0 observations	3 observations

Table 2.4. Median, Mean, and Standard Deviation of Blue Price Prediction Errors*

Treatment	Median	Mean	Standard Deviation
1.1	1.837494	2.950714	25.32024
1.2	0	8.617401	38.75281
1.3	-3.966675	-2.073759	16.10739
2.1	-6.116669	-4.237016	37.26809
2.2	-11.25	-14.71561	34.04646
2.3	-15.125	-16.78208	31.28795
3.1	-71.91666	-54.79001	58.80152
3.2	-18.97093	-17.368399	85.61176
3.3	-24.62798	-27.6472	61.31977
4.1	35.27777	23.24266	34.39106
4.2	38.40973	69.25708	93.31795
4.3	-18.15908	-24.45132	55.09314
5.1	75.46244	63.3893	138.1242
5.2	-169.3971	-68.8563	335.1888
5.3	67.99141	31.08266	112.4778

*For each session a measure of is calculated for each period. This measure is $\beta_t = P_{B,t} - [E(D_{B, T-t+1})]/E(D_{R,T-t+1})]P_{R,t}$ and these terms are defined in Section III.

Table 2.5. Median, Mean, and Standard Deviation of Absolute Blue Price Prediction Errors*

Session	Median	Mean	Standard Deviation
1.1	6.337494	16.06238	19.46022
1.2	9.670639	20.92165	33.45438
1.3	10.31666	12.02804	10.527
2.1	22.09999	28.27567	23.79527
2.2	21.73809	27.23312	24.62583
2.3	19.25	24.96542	24.88618
3.1	71.91666	70.39436	37.35873
3.2	45.59723	63.1231	58.8547
3.3	33.12918	52.52.771	40.74718
4.1	41.21528	37.66548	16.06372
4.2	44.49307	87.14594	75.90591
4.3	29.50357	46.38438	37.41444
5.1	153.3334	132.0724	80.91066
5.2	198.4077	275.5202	248.9735
5.3	48.57314	90.70865	93.83862

*For each session a measure of tightness is calculated for each period. This measure is the absolute value of β_t, where $\beta_t = P_{B,t} - [E(D_{B,\ T\text{-}t+1})]/E(D_{R,T\text{-}t+1})]P_{R,t}$ and these terms are defined in Section III.

Table 2.6 Treatment Averages of Mean Blue Price Prediction Error Bias.*

	Same Variance	Different Variance	Uncertain Exchange	Row Mean
Same Dividends	3.16 (5.349)	-11.91 (6.726)		-4.375
Different Dividends	-33.37 (19.204)	22.68 (46.857)		-5.345
Uncertain Exchange			8.54 (139.263)	8.54
Column Mean	-15.105	5.385	8.54	-0.514

*Mean of means is the first entry in a cell and the associated standard deviation is in braces. For each session a measure of bias is calculated for each period. This measure is $\beta_t = P_{B,t} - [E(D_{B,\,T-t+1})]/E(D_{R,T-t+1})]P_{R,t}$ and these terms are defined in Section III.

Table 2.7 Means of Treatment Median Bias of Blue Price Prediction Errors*

	Same Variance	Different Variance	Uncertain Exchange	Row Mean
Same Dividends	-0.71	-10.83		-5.77
Different Dividends	-38.51	18.51		-10
Uncertain Exchange			-8.65	-8.65
Column Mean	-19.61	3.84	-8.65	-8.14

*For each session a measure of tightness is calculated for each period. This measure is the absolute value of β_t , where $\beta_t = P_{B,t} - [E(D_{B,\,T-t+1})]/E(D_{R,T-t+1})]P_{R,t}$ and these terms are defined in Section III.

Table 2.8 Treatment Mean Prediction Errors and Robust Standard Errors of the Mean Prediction Errors using the Huber/White/sandwich Estimation Procedure*

Treatment	Coefficient	Robust Standard Error	p-value $\beta_i = 0$
1	3.165	3.088	0.33
2	-11.912	3.883	0.012
3	-33.374	11.088	0.013
4	22.683	27.053	0.421
5	-8.648	80.404	0.916

* The parameter estimates are from the regression MPR = $\beta_1 T_1 + \beta_2 T_2 + \beta_3 T_3 + \beta_4 T_4 + \beta_5 T_5$. Where MPR is the mean prediction error as defined in the note to Table 2.4 and $T_1 \ldots T_5$ are 0-1 dummy variables for the five treatments presented in Table 2.3.

Table 2.9 P-values of Pair-Wise Comparison of Treatment Mean Prediction Errors (Bias)

	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5
Treatment 1		0.0125	0.0099	0.4899	0.8862
Treatment 2			0.0977	0.2343	0.9685
Treatment 3				0.0842	0.7669
Treatment 4					0.7196

Table 2.10 Treatment Averages of Mean Absolute Blue Price Prediction Errors

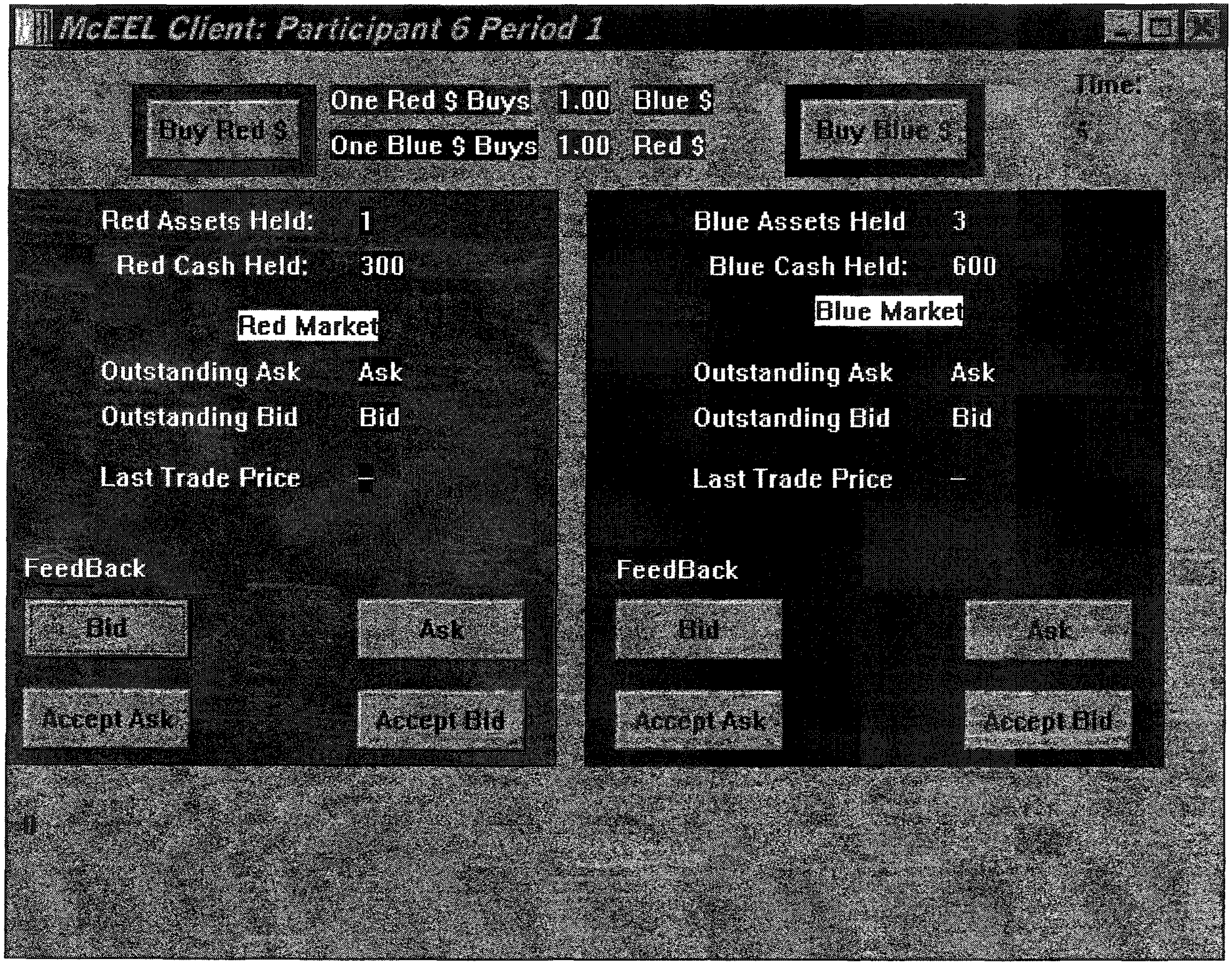
	Same Variance	Different Variance	Uncertain Exchange	Row Mean
Same Dividends	16.34 (21.15)	26.82 (24.44)		21.58
Different Dividends	62.02 (45.65)	57.07 (43.13)		59.545
Uncertain Exchange			166.10 (141.24)	166.1
Column Mean	39.18	41.945	166.1	82.41

Treatment mean absolute prediction error is the first entry in a cell and the associated standard error is in braces. Blue Price Prediction Errors are defined in the note on Table 2.4.

Table 2.11 Treatment Averages of Median Absolute Blue Price Prediction Errors

	Same Variance	Different Variance	Uncertain Exchange	Row Mean
Same Dividends	8.77	21.03		14.9
Different Dividends	50.21	38.4		44.305
Uncertain Exchange			133.44	133.44
Column Mean	29.49	29.715	133.44	64.215

Appendix 2.1
Subject Screen



Appendix 2.1

Double Auction Asset Market Instructions

You are about to participate in an experiment in economic decision making. There are no correct or incorrect responses. Your decisions and the decisions of others will determine how much you are paid at the end of this session. You may earn a substantial amount of money. Funding for this experiment has been provided by the Social Sciences and Humanities Research Council of Canada.

Each of you will be able to act as an asset trader in this experiment. You will be able to buy and sell two different assets, Red Assets and Blue Assets, as you see fit in separate double auction markets. You can think of an asset as being shares in a company which will pay you some dividend every year. An asset gives you some income every time period, in this case every period. In this session there are 2 different types of assets, Red Assets and Blue Assets. Red Assets may be different from Blue Assets.

There will be 20 trading periods in this session. Each trading period in this session will last for 3 minutes or 180 seconds. The time remaining in a trading period will be shown at the upper right hand corner of your computer screen. There will 2 different kinds of money in this environment; Red Dollars and Blue Dollars. Red Dollars are required to buy Red Assets and Blue Dollars are required to buy Blue Assets. At the end of the session your holdings of Blue Dollars will be converted into Red Dollars at the exchange rate shown in the last period. Then your total of Red Dollars will be converted into Canadian Dollars at an exchange rate of 1Canadian Dollar for every 77 Red Dollars.

At the beginning of the session you will receive an endowment. Your endowment will contain some combination of; Red Assets, Blue Assets, Red Dollars, and Blue Dollars. Not all individuals will receive the same endowment.

The return to holding a Red Asset at the end of a trading period will be a dividend of either R$10 or $R20, never any other value. The value of the dividend will be selected by the roll of a die at the end of each trading period. A roll of 1, 2, or 3 will mean a dividend of R$10. A roll of 4, 5, or 6 will mean a dividend of R$20. If you were to hold a Red Asset for a sufficiently long period of time the average return would be R$15 per period. The asset has no value to anyone other than the dividend received at the end of each period. After the dividend has been paid in the 20th period, the asset will not create any more income. All Red Assets are identical. Does everyone understand how the return to the Red Asset is determined?

The return to holding a Blue Asset at the end of a trading period will be a dividend of either B$15 or B$25, never any other value. The value of the dividend will be selected by the roll of a die at the end of each trading period. A roll of 1, 2, or 3 will mean a dividend of B$15. A roll of 4, 5, or 6 will mean a dividend of B$25. If you were to hold a Blue

Asset for a sufficiently long period of time the average return would be B$20 per period. The asset has no value to anyone other than the dividend received at the end of each period. After the dividend has been paid in the 20th period, the asset will not create any more income. All Blue Assets are identical. Does everyone understand how the return to the Blue Asset is determined?
The dividend of the Red Asset and the dividend of the Blue Asset are independent of each other. The dividend on the Red Asset has no impact on what the dividend of the Blue Asset will be. These dividends will be determined by separate rolls of the die.

Please fill in the following chart as the die is rolled. Someone will check your work.

Period	Roll	Red Dividend	Roll	Blue Dividend
1				
2				
3				

The return to holding each type of asset will be revealed to each of you, along with your and only your total income of Red Dollars generated by holding Red Assets and your total income of Blue Dollars generated by holding Blue Assets on a separate screen between trading periods. The dividend to holding either type of asset is the same for all traders. For example, if you receive a dividend of R$20 for each Red Asset you hold, everyone else who holds Red Assets will also receive a dividend of R$20 on each asset.

All endowments will have the same expected value, but some will have different combinations of assets and currencies.

Once you have received your endowment of Red Dollars, Blue Dollars, Red Assets and Blue Assets, there are 10 different actions that you may take.

THE RED ASSET MARKET

THE RED ASSET MARKET HAS A RED BACKGROUND

BIDDING IN THE RED ASSET MARKET (to buy a Red Asset)

Entering a bid is making a request to buy a Red Asset from another trader at a specific price in Red Dollars. For example, entering a bid of R$5 would be the same as asking all of the other traders in the session if one of them would like to give you a Red Asset in exchange for R$5. If someone agrees, you will give them R$5 and they will give you a Red Asset. Making a bid does not guarantee that it will be accepted.

If someone else has already entered a bid, this does not prevent you from entering another bid. The only restriction in this situation is that the bid you enter must be *higher* than the bid already entered by another trader. By the same token, having entered a bid yourself does not prevent you or another trader from entering a higher bid. Once again entering a bid does not guarantee that it will be accepted.

To enter a bid, simply use your computer mouse to press the button market **BID** on the bottom left hand side of the section of your screen with the Red background. Once you have pressed the Red **BID** button, a box will appear in which you can enter your bid using your computer keyboard. Once you are sure that you have entered your bid correctly, press the OK button. The computer will check to see if your bid is acceptable and if it is, it will be posted to the Red Asset market, and a label will appear beside your bid to remind you that you have the outstanding bid.

If your bid is not acceptable for some reason you will be informed of this and the reason why in the Red feedback area identified above the Red **BID** button.

Note that you may not enter a bid in the Red Asset market that is higher than the total Red Dollars you hold.

Whenever you enter a bid it is to buy *ONE* Red Asset.

ASKING IN THE RED ASSET MARKET (to sell a Red Asset)

Entering an ask is offering to sell a Red Asset to any of the other traders in the market at a specific price. For example, entering an ask of R$50 would be the same as asking all other traders in the session if they would like to give you R$50 in exchange for a Red Asset. If someone agrees, you will give them a Red Asset and they will give you R$50. Making an ask does not guarantee that it will be accepted.

If another trader has already entered an ask this does not prevent you from entering an ask of your own. The only restriction is that your ask must be *lower* than the one already entered by another trader. Equivalently, having entered an ask does not prevent you or another trader from entering a lower ask. Once again, entering an ask does not guarantee that it will be accepted.

To enter a ask, simply use your computer mouse to press the button marked **ASK** on the bottom right hand side of the section of your screen with the Red Background. Once you have pressed the Red **ASK** button a box will appear in which you can enter your ask using your keyboard. Once you are sure that you have entered your ask correctly, press the OK button. The computer will check to see if your ask is acceptable and if it is, it will be posted to the Red Asset market, and a label will appear beside the outstanding Red ask to remind you that you have the outstanding ask.

If your bid is not acceptable for some reason you will be informed of this and the reason why in the Red feedback area identified above the Red **ASK** button.

Note that you cannot enter an Ask in the Red Asset market if you do not own any Red Assets.

Whenever you enter an ask it is to sell *ONE* Red Asset.

ACCEPTING AN ASK IN THE RED ASSET MARKET (Purchasing a Red Asset)

Accepting an ask is agreeing to someone's offer to sell you a Red Asset for a specified price. The specified price is the outstanding Red ask shown in the Red section of your computer screen. Remember when you want to ***purchase*** a Red Asset from the trader with the outstanding ask, you want to accept the Red Ask.

To accept the outstanding Red ask simply use your computer mouse to press the button labelled **ACCEPT ASK** on the lower left of the section of your computer screen with the Red background. A box will appear asking you to confirm your purchase of a Red Asset at the price of the outstanding Red ask. If you press OK, you will give the trader with the outstanding ask the price they asked for and they will give you a Red Asset. You will not know with whom you are trading.

Note that you cannot accept an Red ask more for more Red Dollars than you have.

When a Red ask has been accepted, all traders will be informed that a Red transaction has taken place in the Red feedback area of their screens and the Red Last Trade Price will be updated with the price at which the transaction occurred.

ACCEPTING A BID IN THE RED ASSET MARKET (Selling a Red Asset)

Accepting a bid is agreeing to another trader's request to buy a Red Asset for a specified price. The specified price is the outstanding Red bid shown in the Red section of you computer screen. When you want to ***sell*** a Red Asset to another trader you want to accept the outstanding Red bid.

To accept the outstanding Red bid simply use your computer mouse to press the button on the lower right hand side of the Red section of your computer screen labelled **ACCEPT BID**. A box will appear asking you to confirm your sale of a Red Asset at the price of the outstanding Red bid. If you press OK you will give the trader with the outstanding Red bid a Red Asset and they will give you an amount of Red Dollars equal to the outstanding Red bid. You will not know with whom you are trading.

Note that you cannot accept a Red bid if you do not own any Red assets.

When a Red bid has been accepted, all traders will be informed that a Red transaction has taken place in the Red feedback area of the their screens and the Red Last Trade Price will be updated with the price at which the Red transaction occurred.

THE BLUE ASSET MARKET

THE BLUE ASSET MARKET HAS A BLUE BACKGROUND

The Blue Asset market works in exactly the same way as the Red Asset market, except that you use Blue Dollars instead of Red Dollars.

BIDDING IN THE BLUE ASSET MARKET (to buy a Blue Asset)

To enter a bid in the Blue Asset market, simply use your computer mouse to press the button market **BID** on the bottom left hand side of the section of your screen with the Blue background. Then a box will appear in which you can enter your bid using your computer keyboard. Once you are sure that you have entered your bid correctly, press the OK button. If your bid is posted to the market a label will appear beside you bid to remind you that you have the outstanding bid.

If your bid is not acceptable for some reason you will be informed of this and the reason why in the Blue feedback area identified above the Blue **BID** button.

Note that you may not enter a bid in the Blue Asset market that is higher than the total Blue Dollars you hold.

Whenever you enter a bid it is to buy *ONE* Blue Asset.

ASKING IN THE BLUE ASSET MARKET (to sell a Blue Asset)

To enter an ask in the Blue Asset Market, simply use your computer mouse to press the button marked **ASK** on the bottom right hand side of the section of your screen with the Blue Background. Use your keyboard to enter your ask. Once you are sure that you have entered your ask correctly, press the OK button. If your ask is posted to the market a label will appear beside your ask to remind you that you have the outstanding ask.

If your ask is not acceptable for some reason you will be informed of this and the reason why in the Blue feedback area identified above the Blue **ASK** button.

Note that you cannot enter an Ask in the Blue Asset market if you do not own any Blue Assets.

Whenever you enter an ask it is to sell *ONE* Blue Asset.

ACCEPTING AN ASK IN THE BLUE ASSET MARKET (Purchasing a Blue Asset)

To accept the outstanding Blue ask simply use your computer mouse to press the button labelled **ACCEPT ASK** on the lower left of the section of your computer screen with the Blue background. A box will appear asking you to confirm your purchase. If you press OK the transaction will take place.

Note that you cannot accept an Blue ask more for more Blue Dollars than you have.

When a Blue ask has been accepted, all traders will be informed that a Blue transaction has taken place in the Blue feedback area of their screens and the Blue Last Trade Price will be updated with the price at which the transaction occurred.

ACCEPTING A BID IN THE BLUE ASSET MARKET (Selling a Blue Asset)

To accept the outstanding Blue bid simply use your computer mouse to press the button on the lower right hand side of the Blue section of your computer screen labelled **ACCEPT BID**. A box will appear asking you to confirm your sale. If you press OK the transaction will take place.

Note that you cannot accept a Blue bid if you do not own any Blue assets.

When a Blue bid has been accepted, all traders will be informed that a Blue transaction has taken place in the Blue feedback area of the their screens and the Blue Last Trade Price will be updated with the price at which the Blue transaction occurred.

EXCHANGING CURRENCY

The remaining two actions that you may take are to buy Red Dollars or to buy Blue Dollars.

BUYING RED DOLLARS

Buying Red Dollars is the same as trading in your Blue Dollars for Red Dollars. This is the only way you can purchase Red Assets if you have no Red Dollars.

In order to buy Red Dollars simply use your computer mouse to press the button at the top of your computer screen labelled **BUY RED DOLLARS**. This will activate the currency exchange window. Use your keyboard to enter the number of Blue Dollars you would like to trade in for Red Dollars. The exchange window calculates how many Red Dollars you can buy with the number of Blue Dollars you entered in the exchange window. Adjust the number of Blue Dollars you wish to trade in until the exchange window shows the number of Red Dollars you wish to buy. To complete the transaction press the button labelled OK. Your holdings of Blue Dollars will be reduced by the amount shown in the exchange window and your holdings of Red Dollars will be increased by the amount shown in the exchange window.

Note that your purchase of Red Dollars is limited by the number of Blue Dollars you have and the rate at which Blue Dollars trade for Red Dollars.

BUYING BLUE DOLLARS

Buying Blue Dollars is the same as trading in your Red Dollars for Blue Dollars. This is the only way you can purchase Blue Assets if you have no Blue Dollars.

In order to buy Blue Dollars simply use your computer mouse to press the button at the top of your computer screen labelled **BUY BLUE DOLLARS**. This will activate the currency exchange window. Use your keyboard to enter the number of Red Dollars you would like to trade for Blue Dollars. The exchange window calculates how many Blue Dollars you can buy with the number of Red Dollars you entered. Change the number of Red Dollars you wish to trade until the exchange window shows the number of Blue Dollars you wish to buy. To complete the transaction press the button labelled OK. Your holdings of Red Dollars will be reduced by the amount shown in the exchange window and your holdings of Blue Dollars will be increased by the amount shown in the exchange window.

Note that your purchase of Blue Dollars is limited by the number of Red Dollars you have as well as the rate at which Red Dollars trade for Blue Dollars.

THE EXCHANGE RATE BETWEEN RED AND BLUE DOLLARS

Throughout this session the exchange rate between Red Dollars and Blue Dollars will remain fixed at R$1 = B$1. That is to say you may buy 1 Red Dollar for 1 Blue Dollar or 1 Blue Dollar for 1 Red Dollar. This will be the exchange rate for the entire session.

Are there any questions?

Chapter Three
Rate of Return Parity with Robot Traders

Chapter Three
Rate of Return Parity With Robot Traders

I. Introduction

Experimental investigations of asset markets have generated data that have many qualitative similarities. In single asset market experiments the overwhelmingly consistent qualitative observation is that inexperienced traders generate price bubbles. A price bubble occurs when an asset trades at a price well above its fundamental value for an extended period of time. Along with price bubbles are market crashes. In the setting of experimental asset markets this is the term used to describe the rapid descent of contract prices from their bubble level to or below the risk-neutral fundamental value. This pattern of bubbles and crashes is observed in virtually all studies of experimental asset markets which employ inexperienced subjects as traders. See Sunder [1995] for a survey of the experimental asset market literature.

The simultaneous asset markets in Chapter Two have also generated similar qualitative characteristics. The first major qualitative consistency in these experiments is that both asset markets exhibit price bubbles and crashes. The second major qualitative observation is that many of the price bubbles are interrelated, through rate of return parity. In these experiments the bubble growth and collapse phases coincide. More over the price levels in both markets are observed to be strongly related in the simplest treatments.

Informal debriefings of subjects were somewhat frustrating, as subjects were often unable to explain their beliefs about the market outcomes and their own strategies with regard to those outcomes. Some subjects, but definitely not all, did in fact identify that the assets were trading well above the risk neutral expected dividend value, but choose to buy at those prices anyway. Obviously, this behaviour is not explained by strictly rational expectations in conjunction with common knowledge of rationality. If all individuals trade based on strictly rational expectations of the expected dividend, there would be no trades at all, let alone trades at prices well above the sum of the expected dividends. In this essay simple behaviour rules applied to robot traders are employed to help understand the outcomes from a single environment in which two assets were traded simultaneously.

If a population of robot traders can generate data qualitatively similar to that of previous simultaneous asset market experiments, then some understanding of the behaviour of human subjects may be gained. In the worst case scenario, some conjectures about behavioural rules may be excluded from future research. If a behavioural rule does not generate data with the appropriate qualitative properties when applied unerringly, it is not a good candidate for describing the behaviour of human subjects.

The studies using simultaneous experimental asset markets, Fisher and Kelly [2000] and the previous chapter of this thesis, have concluded that prices of assets with uncertain dividends in the two markets are frequently consistently linked, independent of rate of return parity between assets with uncertain dividends and currency. However, these studies have found support for the existence of rate of return rarity between two assets with uncertain dividends. This finding is based on the assumption that the expected capital gains associated with both the assets with uncertain dividends are equal. In the preceding chapter this was motivated by having agents who have time horizons that extend to the end of the session. As was noted in a footnote, it is not essential for rate of return parity as described above that agents have time horizons that extend to the end of the session, only that they equate expected capital gains[9]. This more general approach will be applied to robot arbitrageurs used in this essay.

If a plausible behavioural rule applied to robot traders can accurately recreate the behaviour of human subjects in the laboratory we may conjecture that we have discovered a behavioural rule which characterizes the actions of these human subjects. This finding is by no means conclusive, however. It remains possible that subjects in an experimental environment were following some other behaviour rule and not any of the types of behaviour included in this essay. This testing procedure is by no means exhaustive.

This approach to investigating experimental markets was first used by Gode and Sunder [1993]. The authors investigate the allocative efficiency of double-auction goods markets with zero-intelligence robot traders. These robot traders were programmed to enter random bids if they were designated as buyers or random asks if they were designated as sellers. All bids and asks were subject to the standard improvement rule. This rule in double auction markets states that any new bids must be higher than the preceding bid and any new asks must be lower than the preceding ask. Once a simple no-loss rule was imposed on these traders the investigators report that markets populated by this type of robot traders approach perfect allocative efficiency.

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[9] This approach is somewhat at odds with a recent work by Lei, Noussair, and Plott [2000] in which price bubbles in double auction markets for multi-period lived assets are observed even when there is no possibility to earn capital gains. Future research might attempt to use the no capital gains environment created in this paper to study rate of return parity.

Price bubbles in goods markets have also been investigated using robot traders. Steiglitz and Shapiro [1998] use a variety of computerized behavioural algorithms, or robots with different behavioural rules, to populate a call market. Cason and Friedman [1997] focus on the formation of prices in call markets populated by robot traders. Mizuta, Steiglitz and Lirov [1999] consider the impact of price signal choices on market stability using robot traders.

The relationship between two simultaneous asset markets in which the assets have the same expected dividend., the same distribution of possible dividends, and a perfectly fixed exchange rate (Treatment 1 in Chapter Two) will be explored in a situation when the two asset markets are populated by robot traders which follow known behavioural rules. The specific types of rules followed by the robot traders are described are in Section II. The goal of this essay is to create data that mimics the qualitative features of human populated dual asset market sessions: specifically the bubbles and crashes and the co-ordination of price bubbles and crashes. Unless otherwise indicated, all robots populating a given market will follow the same behavioural rules. This is done for simplicity.

The heuristics governing robot behaviour in this essay were intended to be simple, and were by no means intended to be exhaustive. The first heuristic employed is expected dividend value pricing. This type of behaviour is often used as the bench mark against which the pricing behaviour of human populated asset markets are compared. The prediction of this type of behaviour is that per period average transaction prices will follow the risk neutral expected value of dividends. This type of heuristic is included to demonstrate that the robot populated markets will in fact produce this result. In some ways this population can be thought of as control group or calibration group to demonstrate that robot traders are behaving as predicted. The second behavioural rule is adaptive expectations. This heuristic is one of the many ways in which expectations might be modelled. It is included in this essay, to demonstrate such a behavioural rule will not produce bubbles that are consistent with human populated markets in size or duration. The mismatch in size in duration is motivated largely be the fact that these price bubbles are not expected to crash. Further more, there is no reason to expect that robots using adaptive expectations will produce rate of return parity between assets with uncertain dividends. Again this type of robot serves almost as a calibration group for the robot population. The third heuristic robot traders were programmed to follow was to generate bid and ask values for the assets based on a weighted average of trend in prices and the expected dividend value, and then use one of these values after randomly choosing to place a bid or ask. This heuristic was included to demonstrate that this type of behaviour can and does create bubbles of similar size and duration to markets populated by humans. Again there is no reason to expect that this robot population will produce data in which rate of return parity can be observed. The fourth behavioural rule included was profit maximizing weighted average trend pricing. These robots calculate the expected profit of all actions and then choose the most profitable. This heuristic was included to demonstrate that it can and does create bubbles similar to those produced by human traders. This heuristic is not expected to generate rate of return parity between assets with uncertain dividends. The final heuristic that the robots discussed in this essay followed was that of simple arbitrage. These robots compared the prices of the assets between the two markets and then traded to take advantage of any opportunities for cross market arbitrage. This behavioural rule was incorporated into the robot populations to demonstrate that a relatively small number of arbitrageurs can generate rate of return rarity between assets with uncertain dividends.

II. Description of Robot Traders.

A. Introduction

All sessions used a modified version of the software developed to generate the data presented in Chapter Two. This software was used so that the institutions of that investigation would be identical for robot and human traders. Unless otherwise stated no robot trader transferred currency between markets. Thus funds gained from the sale of Blue Assets were neither used to finance the purchase of Red Assets, nor vice versa. For all traders other than the arbitrageur the values of the assets to the robots were not explicitly linked. Other than the designated arbitrageur the robots neither used the price of the Red asset in determining the value of the Blue Asset, nor the price of the Blue Asset in determining the value of the Red Asset. The characteristics of the assets are identical to Treatment 1 in Chapter Two. The Red and Blue assets in robot populated sessions have exactly the same risk neutral expected value and the exact same variance in dividends.

Each robot trader was randomly assigned a risk attitude so that the value each robot was willing to pay for an asset was between the minimum possible dividend value and the maximum possible dividend value in each period of the simulation. There were two central reasons for this. The first, is that in an asset environment there is no parallel to redemption values. In order to generate trades in this type of environment there must be some difference in the values different agents assign to the asset in question. The second reason is that subjects in the human populated market also exhibit varying degrees of risk aversion. The manner for eliciting the degree of risk aversion is discussed below.

B. Measuring Risk Attitudes

Before the markets opened in each session of the experiment presented in Chapter Two, subjects' risk attitudes were elicited using the method proposed by Becker, DeGroot, and Marschak [1964], later modified by Harrison [1986]. Subjects were given the rights to a binary lottery. Subjects are then asked to state the lowest price at which they would be willing to sell their rights to the lottery. A random buying price is generated and if the random buying price is greater than the selling price entered by the subject the subject sells the rights to the lottery for the randomly generated price. If the randomly generated buying price is lower than the price entered by the subject, the subject plays the lottery. Another random number is generated, if this random number is lower than the probability of winning the lottery the subject wins a monetary prize, if this random number is greater than the probability of winning the lottery the subject receives nothing. Each subject provides prices for 10 lotteries. The selling price entered by the subject in each lottery can then be used as a certainty equivalent for determining the risk attitude of the subject. The instructions for this part of the experiment are included as Appendix 3.1

Risk attitudes elicited from subjects are presented in Table 3.1. These risk attitudes are by no means the same across subjects, some are risk averse and other are risk loving. Thus it is not unreasonable to use robots with randomly assigned risk attitudes to be similar to the risk attitudes of human subjects. The data in Table 3.1 are the average ratios of the minimum selling price entered by subjects in the Becker, DeGroot, and Marshak tests described above. Any entry less than 1 indicates that the subject was risk averse, their average minimum selling price for the lottery was less than the risk neutral expected value. Any entry in Table 3.1 greater than 1 indicates that the subject was risk loving, their average minimum selling price for the lottery was greater than the risk neutral expected value.

C. Zero Intelligence Robot Traders (ZIT's)

The zero intelligence robot traders under a no loss condition will form the baseline for these simulations. This type of trader is very similar to that used by Gode and Sunder [1993], who assigned each trader a different production cost or redemption value, as is commonly done with human traders. The application of different risk attitudes is not without further grounding in human behaviour observed in the laboratory. In many studies of risk attitudes as well as in the work presented above, the individuals participating in the experiment displayed a range of risk aversion measures. This characteristic has therefore been incorporated into each of the ten the robot traders used for this investigation.

The ZIT's are programmed to randomly choose between the red and blue markets.

Once having chosen which market to consider the computerized traders randomly choose between bidding and asking. Once having selected a market and action, the robot traders randomly generate a bid or ask between the outstanding bid or ask and the individual trader's fundamental value. If the trader had randomly selected bid and the outstanding bid was greater than the trader's fundamental value then that trader accepted the outstanding bid, becoming a seller rather than a buyer. Similarly if the trader had chosen ask and the outstanding ask was below the fundamental value the trader accepted the outstanding ask, becoming a buyer rather than a seller. The fundamental value used by traders is described in Equation (3.1)

$$DividendValue = (T - t + 1) \cdot (15 + RA) \qquad (3.1)$$

Where T is the number of periods in the session, t is the current period, 15 is the risk neutral expected dividend in each period, and x is the risk attitude randomly assigned to the robot trader, such that $-5 \leq RA \leq 5$.

The general process is described in Figure 3.1 below. When there are double arrows, the choice between cells is determined by the specific nature of the robots. The random choice robots will choose between each cell with equal probability.

D. Adaptive Expectations Robot Traders (AET's)

An expectations process that has been commonly used in macroeconomics is adaptive expectations.[10] Agents with adaptive expectations start with some preconceived

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[10] The use of adaptive expectations has fallen out of fashion since the early 1980's in favour of rational expectations. The traders described as ZITs could be thought of as rational expectations traders.

expectation of the value of some variables. In this particular case the variables are the price of the Red Asset and the price of the Blue Asset. Adaptive expectations agents then update their expected values after a realization, in this case a transaction. The update is based on some proportion of the difference between the realized value and their expectation. An example of an adaptive expectations process can be seen in equation (3.2).

$$E(P(t)) = P(t-1) + \lambda(P(t-1) - E(P(t-1))) \tag{3.2}$$

E(P(t)) is the current expected price, P(t-1) is the actual price of the previous transaction, lambda is the adjustment parameter that has a value between zero and unity. The AET's in the computerized asset markets run here form price expectations according to equation (3.1) with $\lambda=0.5$. The initial price is determined by combining the expected dividend value of the asset in the first period with the robots' randomly assigned risk attitude. The AET's use the same decision process as ZIT's described in Figure 3.1.

E. Random Action Weighted Average Trend Robot Traders (RAWAT's)

Price bubbles and crashes have long presented a difficulty for any individual attempting to explain the behaviour of humans in laboratory asset markets. The existence of price bubbles is often taken as evidence of irrationality of subjects and as such has proven very difficult to model. Smith, Suhanek, and Williams [1988] conducted an intensive examination of laboratory asset market price bubbles and crashes with only moderate success. The finding that price bubbles are reduced in size and frequency as subjects gain experience, does not entirely explain why price bubbles formed in the first place. Steiglitz and Shapiro [1998] simulate goods market price bubbles using "trend-based" traders. These traders predict the future prices as a weighted average of past transaction prices. The "trend-based" traders do generate some price bubbles. A similar type of robot trader (RAWATs) populates the asset markets in this case.

Each trader first generates a prior belief about the value of the asset. This prior is based solely on the traders randomly assigned risk attitude and the expected value of the dividend stream from holding an asset. This is the same as the value calculated by the ZITs and the initial value calculated by AET's as described above. The first trades between robots of this type will be governed by these values. Once trades begin to occur, robots calculate a trend term to the value of the asset to form a component of the value of the asset. This trend term is shown in equation (3.3).

$$\text{trend} = 0.7(P_{t-1} - P_{t-2}) + 0.5((P_{t-2} - P_{t-3}) + 0.3((P_{t-3} - P_{t-4}) \qquad (3.3)$$

If fewer than 4 trades have occurred then the third term in equation (3.3) is set to zero[11]. Similarly the second and third terms are also set to zero if fewer than three trades have taken place. The weights on the trends are not adjusted when fewer than four trades had taken place. This was done for ease of programming. Further the trend terms are not period specific, the robots make no distinction over when the previous trades occurred. Once traders begin to calculate trend values, a robot's total value of the asset is a weighted average of the expected dividend value of the asset and the trend value of the asset. The weight placed on the expected dividend value of the asset, w, is equal to the

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[11] The parameter values in Equation (3.3) are completely arbitrary. It is however, intuitively appealing that the weights associated with past trades decline as more trades occur.

number of periods that have elapsed divided by the total number of periods in the session. The weight placed on the trend value is (1- w). With this weighting function the importance of the risk-adjusted expected dividend value of the asset increases as each trading period passes. These robots used exactly the same weighting process to determine the value of both the Red and Blue Assets. Thus the value each robot assigned to an asset was calculated as

$$V_R = \frac{T-t_i}{T}(trend) + \frac{t_i}{T}(dividend\ value) \tag{3.4}$$

Where T represents the number of trading periods in the session and t_i represents the current trading period. The overall process of choosing which market in which to take action is identical to that described in Figure 3.1.

F. Profit Maximizing Weighted Average Trend Robot Traders (PMWATs)

It order to address the possibility that the RAWATs generate separate bubbles which are solely a function of the random choice of action, robots that choose their action based on the profitability of their potential actions are developed. Each robot generates a random bid and ask for each of the asset markets. The PMWATs then calculate the profitability of entering the bid or ask. The profitability of an action is calculated as

$$\textit{Bidder Profit} = \textit{Value} - \textit{Bid}$$
$$\textit{Asker Profit} = \textit{Value} - \textit{Ask}$$

Whichever action leads to greater profit is under taken. Thus while the choice between bid or ask maximized expected profit, the selection of the specific bid or ask is not part of the optimization procedure.

These robots calculate the value of the assets in exactly the same way as did the RAWAT's. When considering the profitability of a bid or ask, robots assume that any bid or ask entered will be accepted. This rule was adopted for simplicity and adopting any other rule would have been just as arbitrary. The choice of which market to participate in made by these robots is now dependent on the value each trader places on the asset in question as well as the spread between the outstanding bids and asks. This process is described in Figure 3.2 below.

F. The Arbitrageur

Given the possibility that the robot traders discussed so far may not lead to the creation of data with the two key qualitative elements, (bubbles of limited size, and rate of return parity over the prices of assets with uncertain dividends) a single arbitrageur is introduced into environments which generate bubbles of size and duration that is comparable to human populated markets. This arbitrageur is quite simplistic. The arbitrageur will take action when the outstanding bid in one market is above the outstanding ask in the other market. If the arbitrageur holds the asset with the high bid it will then sell that asset, transfer the proceeds to the other market and purchase the other asset at the outstanding ask, and keep the difference. If the agent does not hold any of the higher priced assets it will simply purchase the lower priced asset. Implicitly, this robot is acting in complete accordance with the theoretic description of rate of return parity in Chapter Two. This robot has simply equated the expected capital gains on the two assets with uncertain dividends and is acting to maximizing the value of its holdings in light of this equality. A pseudo computer code interpretation of this behavioural rule would be;

If RedBid > BlueAsk
Then Sell Red and Buy Blue
If BlueBid >RedAsk
Then Sell Blue and Buy Red

All other traders in these markets are either RAWATs or PMWATs as these traders are expected to produce price series with bubbles of size and duration comparable to human populated markets. The interaction of the arbitrageur and the value structure of the RAWATs or PMWATs will likely be sufficient to create a link between the two asset prices. If this single arbitrageur can cause the price data to exhibit rate of return parity between the prices of assets with uncertain dividends in spite of the price bubbles, one may expect this sort of rate of return parity in naturally occurring markets as only a small portion of agents would need to be arbitrageurs for the result to be observed.

III. Data and Analysis

A. Introduction

Each session with robot traders consisted of twenty periods. Each of these periods was 20 seconds long. The data analysed is comparable to the data analysed from human populated laboratory markets. The unit of observation will be the average transaction price in each period. If no transaction occurs in a given period the mid-point between the outstanding bid and ask is used as a proxy. The average transaction price is used to overcome a matching problem. Unless transactions occur at exactly the same moment in time in both markets there is no immediately obvious match between the price in the Red Asset market and the price in the Blue Asset market.

Each population of robot traders was used to generate thirty sessions of data, for a total 600 data points per robot population. This meant the simulations ran for approximately 20 hours. 30 sessions per population are chosen to maximize the statistical significance in the face of a computational cost constraint. After each session all software was shut down and then restarted. This meant that the risk attitudes were regenerated for each session.

When analysing the data, two considerations were paramount. The first consideration was the formation of price bubbles. Any population of robot traders that does not consistently generate price bubbles of a size and duration similar to human populated markets does not capture an important element of the human populated markets. The second consideration was the appearance of rate of return parity in the prices of assets with uncertain dividends. In all the human populated markets with identical assets, rate of return parity was observed to hold. Thus if rate of return parity is not observed in the robot populated markets, a key element is absent from the robot behaviour. Figure 3.3 shows the average transaction prices in each period for the human populated markets for Treatment 1 of Chapter Two. Figures 3.4 through 3.9 below show the average transaction prices from one representative[12] session of each robot population.

In order to consider the possible existence of price bubbles it is necessary to develop a metric to measure price bubbles and identify when they are significant. Fisher

[12] The price series shown in Figures 3.4 through 3.9 are reasonably representative of each type of robot. The price data from each robot session will be slightly different due to different risk values assigned to the robots as well as any difference in trade history.

and Kelly [2000] provide a starting point for a price bubbles metric. They suggest that a price bubble can be described by the percentage deviation of price from the risk-neutral expected dividend value of an asset. While this measure will allow for positive and negative price bubbles to be recognized, it is a static measure. This metric only describes the price bubble at a given point of time, but does not allow for a single metric over all periods of a session. A simple sum of the bubble measures over the course of a session will not suffice either, as positive and negative bubbles could possibly offset, resulting in a measure of zero. Using either the sum of the squared price deviations or the sum of the absolute values is not entirely satisfying either. It ignores the time element of price bubbles. A price bubble requires that the price of the asset rise well above its fundamental value and remain there for an extended period of time. The size as measured by the sum of the absolute value of price deviations above or below fundamental values as a proportion of the fundament value. The size of the bubbles are calculated as Equation (3.4)

$$\beta = \Sigma_{t=1}^{20}\left|\frac{P_{n,t} - f_{n,t}}{f_{n,t}}\right| \qquad (3.4)$$

Where β represents the bubble metric, $P_{n,t}$ represents the price of asset n (Red or Blue) in period t (from 1 to 20), $f_{n,t}$ represents the risk neutral expected dividend value of the asset in period t. At first it appears that is definition of a price bubbles is at odds with the work of Smith, Suchanek, and Williams [1988]. If one considers that the central issue behind a price bubbles is significant deviation of the price of an asset from its risk neutral expected dividend value, both positive and negative deviations need to be considered. In the vast majority of human populated laboratory markets, positive deviations from risk neutral fundamental asset value are observed. Thus, it is only natural that descriptions of price bubbles based on the laboratory results focus primarily on positive deviations.

The duration of a price bubble is also important. In this environment the duration of bubbles during a session will be the number of consecutive periods that the price of the asset is more than 33.3% above or below its fundamental risk-neutral value[13].

Considering the issue of rate of return parity is not without difficulties. Many previous investigations of rate of return parity, interest rate parity, and free capital mobility have used a number of different techniques to attempt to describe the relationship between asset prices. For the proposes of this investigation, two approaches based on individual session deviations of P_B , given P_R obtained from equation (3.4) are used.

$$P_B = P_R \tag{3.4}$$

Equation (3.4) is a simplification of Equation (2.10) from Chapter Two. In all the robot populated markets, the expected dividends of the Red and Blue Assets are equal, therefore the ratio of expected dividends is one and can be excluded from the Equation (3.4) without loss of predictive power. In keeping with the work of Chapter Two, first the bias of the relationship is considered. In the human populated markets with identical assets presented in Chapter 2, no bias was found. Second the tightness of arbitrage must be considered. Thus the absolute deviations from equation 3.4 must be considered.

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[13] 33.3% represents the boundary that could be due to risk preference. The risk neutral expected value of the asset is 15 per period, and robots can have risk preferences that cause them to value the asset from 20 to10 per period.

Exact randomization tests [Moir 1998] are employed to address any differences of bias and tightness of arbitrage between robot and human populated markets.

B. Price Bubbles

The sessions from Treatment 1 in Chapter Two have an environment comparable to the sessions populated here by robot traders. The expected dividend is the same for the Red and Blue Assets and the variance of the expected dividends is also the same for both assets. Figures 3.4 through 3.9 above show the average transaction prices in both the red and blue asset markets along with the risk neutral expected value for each period in the lefthand panels. The right hand panels show the difference between the average prices in each period of the Blue and Red Assets, or equivalently the deviation of the Blue Asset price from Equation (3.4). The corresponding bubble metrics are presented in Table 3.2.

The bubble metrics proposed are satisfying in that the numerical results coincide with the visual representation of the data. Session 1 has the largest price bubble and Session 2 the smallest, as is shown in both the graphic presentation and the bubble metrics. Session 1 and Session 3 have bubbles of similar durations while Session 2 has only a small negative price bubble during the early periods.

Table 3.3 below shows the average bubble statistics of all sessions for the robot populated session by type of robot trader. The complete bubble metrics for individual robot sessions are included in Appendix 3.2.

The bubble metrics presented in Table 3.3 above and in Appendix 3.2, illustrate some of the interesting characteristics of the price bubbles formed by the various types of robot traders. First notice that the Zero Intelligence robots do not create large price bubbles in either market, nor do these price bubbles endure for a substantial length of time. This is not surprising given that these robots are essentially rational expectations driven. From this stand point we can say with a fair degree of certainty that human subjects participating in multi period asset market experiments are not all using rational expectations. This result is reassuring for the use of robot traders. The ZITs were fully expected not to create data that was qualitatively similar to human populated marekts. The AETs do create price bubbles of large size and duration. In fact the price bubbles generated by this type of robotic trader are the largest created by any of the types of robots used, or even human populated markets. This is likely in part due to the fact the price bubbles generated in markets populated by adaptive expectations based robots do not return to the fundamental value of the asset towards the end of the session. This fact also allows the conclusion that markets populated by this type of robot do not capture the characteristics of ones populated by humans. Once again this is encouraging for the use of robots as a means to investigate human behaviour. The AETs were expected to create bubbles that were larger than human populated markets.

The RAWATs and PMWATs do produce bubbles of substantive size and duration. The size and duration of these price bubbles appears to be very similar to those of human populated markets. These markets do resemble the characteristics of human populated experimental asset markets in terms of price bubbles.

The RAWATs combined with a single arbitrageur and PMWATs with an arbitrageur also create bubbles of fair size and duration. This type of robot populated market also captures the bubble characteristics of human populated markets. Thus, this type of robot also captures important features of human populated markets.

These bubbles can be compared in size to the bubbles and duration to the bubbles generated in human populated markets using exact randomization tests with a null hypothesis of no difference is the measures of size of price bubble or duration of price bubble. The alternate hypotheses for these tests are different depending on the type of robot being considered. When comparing ZIT's to human populated markets the alternate hypothesis is bubbles metrics in human populated markets will exceed those of ZIT's. This alternate hypothesis means that a one tailed exact randomization test is being used. When AET's are considered, the alternate hypothesis is bubble metrics of the AET's will exceed those of human populated markets in both categories. Again, a one tailed test must be used in each of these cases. For the remaining robot types two tailed tests must be used as there is no theoretical reason to believe that these robots will produce bubbles of small or greater size, or of greater or lesser duration. These results are presented in Table 3.4.

The discussion of the size of bubbles above is largely supported by the exact randomization test results. The ZIT's and AET's produce bubbles that differ significantly in size from those of human populations, with the ZIT's producing smaller bubbles and the AET's producing larger bubbles. The RAWAT's, PMWAT's, RAWAT's with an arbitrageur produce bubbles of a size that is not significantly different from those of human populated markets. The PMWAT's with an arbitrageur produce bubbles of a size that is not significantly different from those of human populations in the Red Asset market. The bubbles produced by this type of robot trader are significantly smaller than human populations in the Blue Asset market however. This is only one aspect of bubbles however.

The results of the exact randomization tests support the initial impression as discussed above. The ZIT's and AET's produce bubbles that have significantly different durations than humans. The RAWAT's, PMWAT's, RAWAT's with an arbitrageur, and PMWAT's with an arbitrageur all produce bubbles that do not differ from human generated bubbles in duration.

As ZIT's and AET's produce bubbles that are significantly different from humans, one can conclude that humans do not behave in accordance with these heuristics. Accordingly, the ZIT's and AET's will be excluded from further discussion. The remaining robots produce bubbles that are not significantly different from those of humans, generally. Thus, it remains possible that these heuristics capture the behaviour of human traders.

C. Rate of Return Parity

Along with price bubbles, for robot populated markets to be comparable to human populated markets must exhibit rate of return parity. Any attempt to use robot traders to generate data of a similar nature must also result in the observation of rate of return parity as well as price bubbles of similar size and duration. Whether or not the robot populated markets exhibit rate of return parity will be discussed in this section, beginning with an examination of the human populated markets, the data for which is presented in Table 3.5

below, followed by an examination of each of the markets populated by each different type of robot.

Appendix 3.3 to this chapter contains the session by session median, mean, and standard deviation of the price of the Blue Asset from its rate of return parity value for robot populated markets. This data is summarized below in Table 3.6. The absolute value of the prediction error of rate of return parity is also important. The complete data is presented in Appendix 3.3, and is summarized in Table 3.7.

Exact randomization tests were applied to the median prediction error and the absolute value of median prediction errors to consider any differences in bias and degree of arbitrage. Bias in rate of return parity can be described as a consistent over or under prediction of the relative asset prices. Bias will be observed as consistently negative or consistently positive prediction errors. The degree of arbitrage or "tightness" of arbitrage is the general accuracy of rate of return parity in predicting relative asset prices. The degree of arbitrage will be observed as the magnitude of the rate of return parity prediction error, in absentia of the direction of the prediction error. The results of these two tailed tests are summarized in Table 3.8.

It should not be surprising that the exact randomization tests presented in Table 3.8 indicate that there is no difference in the bias of the rate of return parity prediction errors. In Chapter Two it was found that there was no bias of the prediction errors in Treatment 1. There is also no reason to believe that the robot populated markets would produce a bias different from zero, as no bias was programmed into the behaviour of the robots. It would have been very surprising indeed if a significant difference in bias was found.

The degree to which rate of return parity is observed as measured by the absolute prediction error is a different question, however. In the two robot populations without arbitrageurs, it was found that the absolute value of prediction errors was significantly different than in the human populations, see Table 3.8. In both cases arbitrage was less complete in markets with robot traders than in markets with human traders. This is not surprising, however, because the robot traders were not provided with the ability to take advantage of arbitrage opportunities.

Including an arbitrageur does improve the performance of the RAWAT's on this criterion, but not sufficiently to bring them in line with the human traders. The exact randomization tests still support the conclusion that the predictions errors of rate of return parity are significantly different in this robot population than in the human population.

The inclusion of an arbitrageur does significantly improve the performance of the rate of return parity prediction in PMWAT populated markets. The exact randomization tests do not indicate that there is a significant difference in the size of the absolute prediction error between these markets and the human populated markets.

Based on the overall performance of the various robot populations compared to the human populations, one can conclude that the PMWAT's with a single arbitrageur closely resembles the human populated markets. This robot population differs significantly from the human population only in terms of the magnitude of the Blue Asset market price bubble. In all other criteria considered; bubble duration, bias of rate of return parity prediction errors, and the absolute value of rate of return parity prediction errors, the PMWAT's with a single arbitrageur was not found to differ from human populations significantly.

IV. Conclusion

The purpose of this chapter is to attempt to generate price data, using robot traders applying known behavioural rules, that resemble the price data generated by human traders in experimental dual asset markets. This can aid in the search for understanding of what behavioural rules human subjects may be applying in this type of market. The key characteristics of price data were the existence of price bubbles and crashes and rate of return parity. Robot traders were created in which these characteristics were observed to a degree similar to that of the human populated markets.

Generating price bubbles of comparable size to human traders required the use of trend based traders. These traders calculated how much they were willing to pay for an asset or conversely how much they were willing to accept for an asset in part by considering the recent price changes. Bubbles of limited size were induced by having these traders increase the weight they placed on the fundamental value of the assets as the end of the session drew nearer. This type of robot was referred to as weighted average trend based traders.

Rate of return parity required the existence of an arbitrageur. The arbitrageur introduced into these markets was quite naive, only considering the existing spread between the outstanding bid in one market and the outstanding ask in the other. In spite of this naivety, a single arbitrageur was able to induce a price pattern consistent with markets populated by human traders when put in markets in which the remainder of the agents were profit maximizing weighted average trend traders.

The comparability of the robot trader populated markets was further improved by a profit maximizing rule. Profit maximizing robot traders one of whom was an arbitrageur was the most similar to the human populations of Chapter Two. The implication of this finding is that some degree of profit maximization is likely happening in human populated markets. Overall, it appears that humans participating in this type of experimental market are forward looking and performing some form of maximization.

If actual asset markets are populated primarily by trend pricing traders, a small number of active arbitrageurs can result in rate of return parity. Failure to observe rate of return parity in naturally occurring asset markets may be caused by an insufficient number of effective arbitrageurs, or by barriers to arbitrage. Future empirical investigations of field data on rate of return parity may profit by focussing on arbitrage opportunities and the barriers to complete arbitrage.

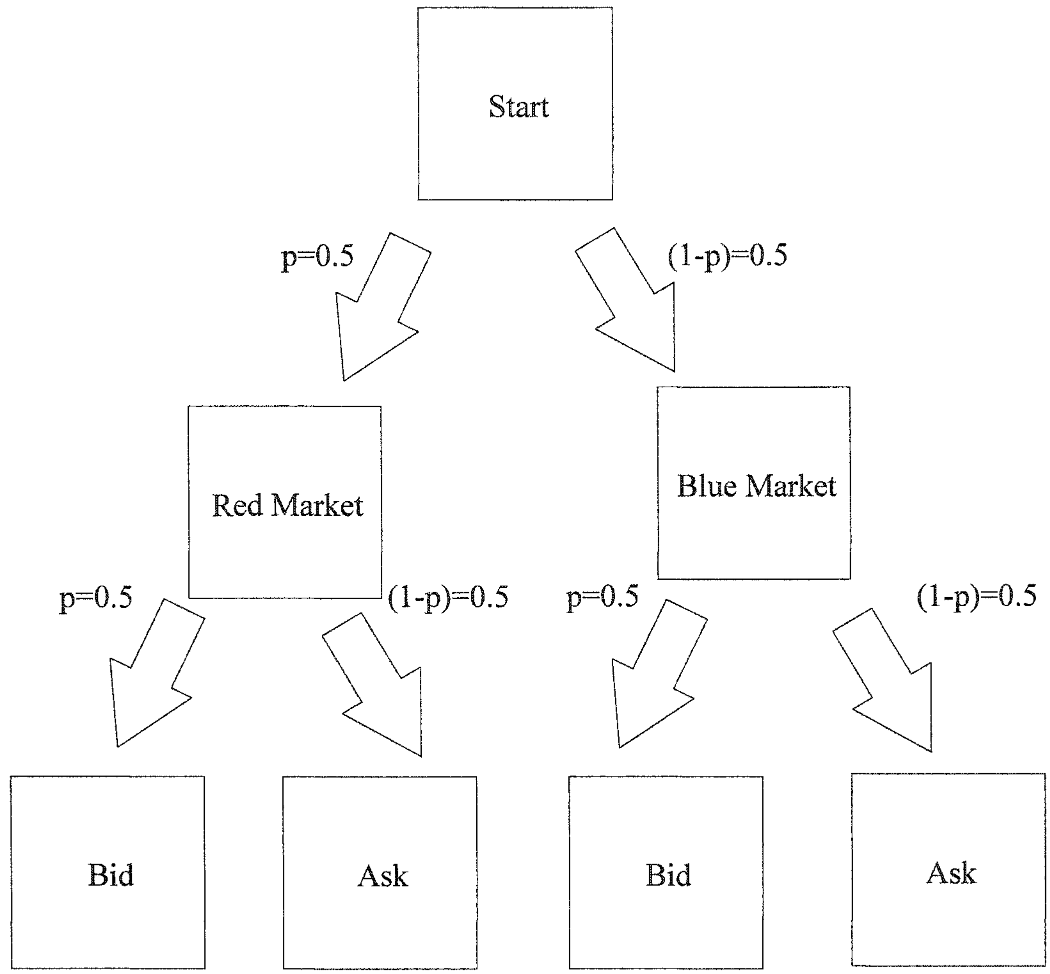

Figure 3.1. Flow Chart of ZIT Robot Behaviour

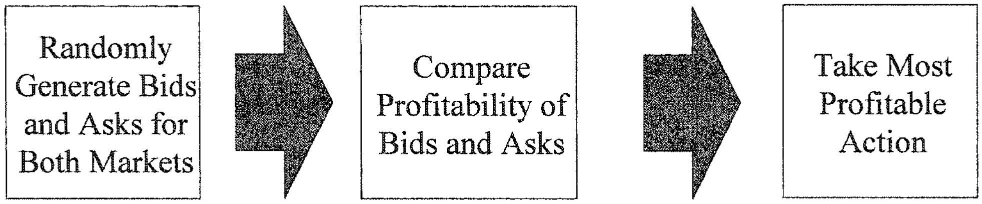

Figure 3.2. Decision Process for PMWAT's

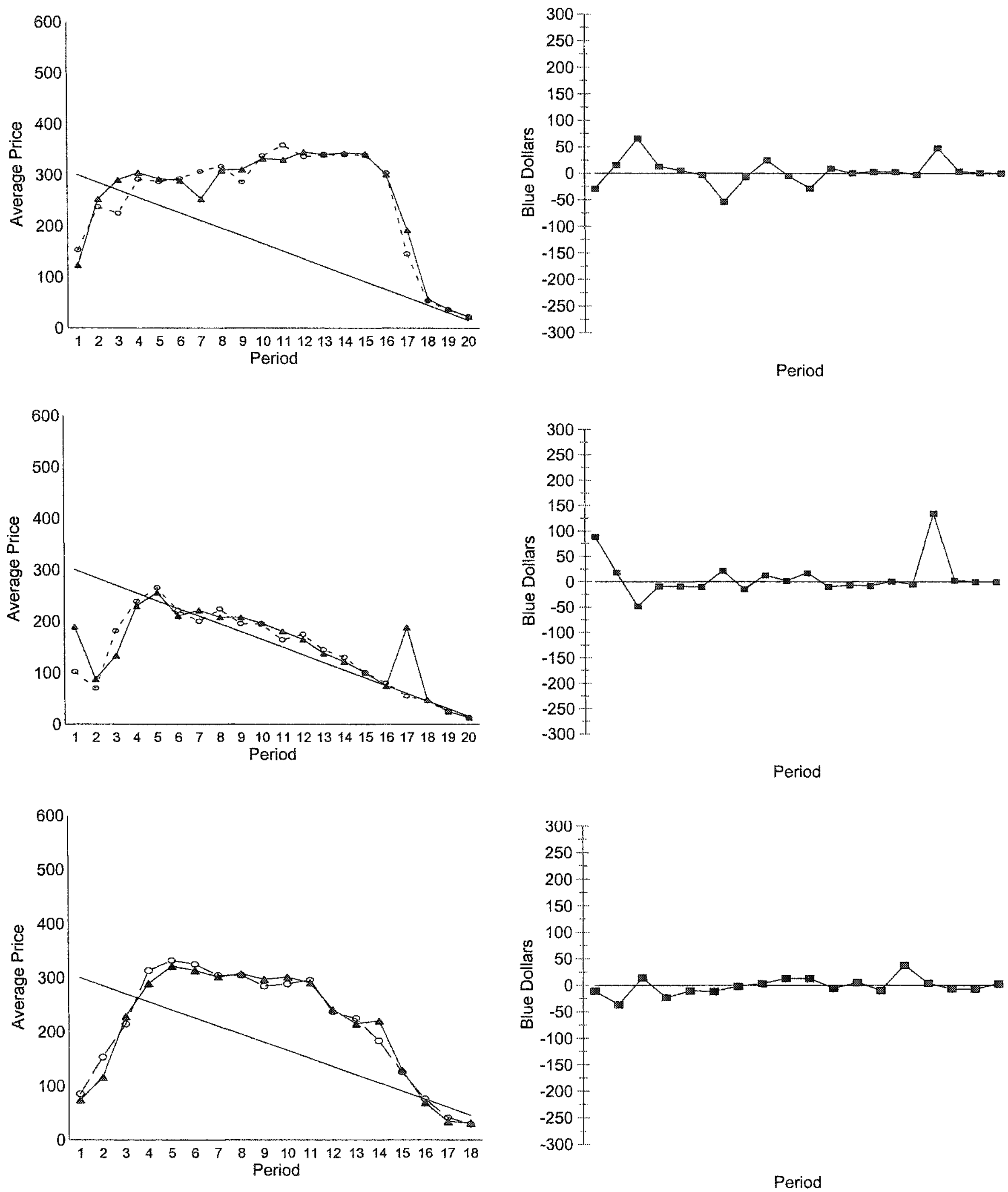

Fig. 3.3. Treatment 1, Sessions 1.1, 1.2 and 1.3 (Top to Bottom); Triangles are Blue Assets, Circles are Red Assets; Downward sloping lines in panels on the left identify fundamental asset values. Right-hand panels display differences between blue asset prices and the rate of return parity predicted value.

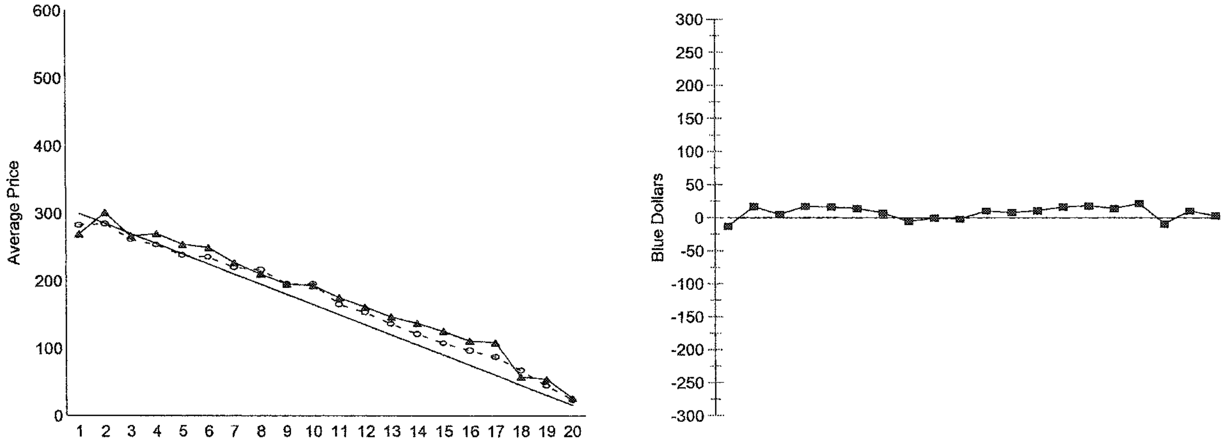

Figure 3.4. Zero Intelligence Traders average price and deviation from Rate of Return Parity. In the right hand panel the open circles represent the average price per period of the Red Asset, the closed triangles represent the average per period of the Blue Asset, and the solid line represents the risk neutral expected value of both assets. In the left hand panel the closed squares represent actual deviations from Rate of Return Parity, and the solid line represents zero deviation from Rate of Return Parity.

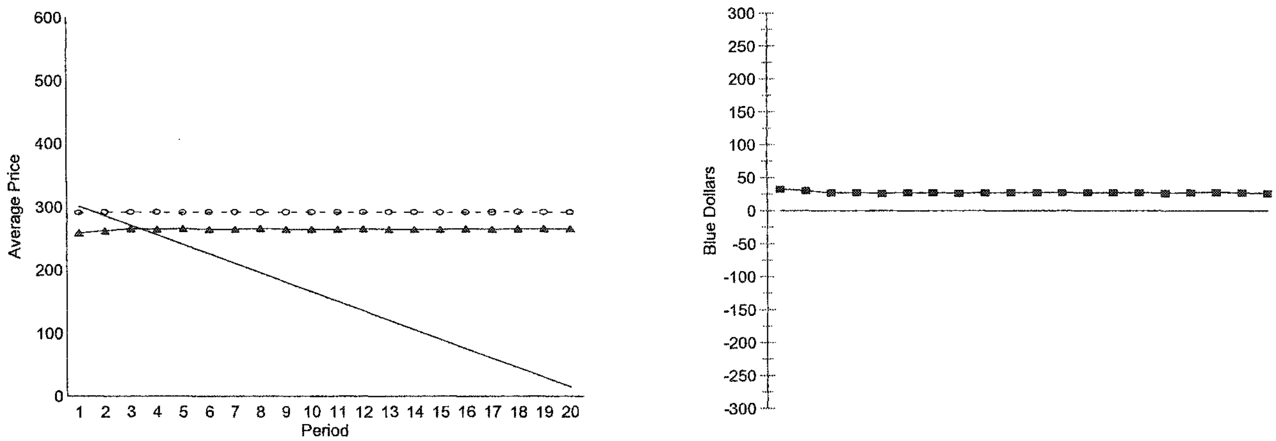

Figure 3.5. Adaptive Expectations Robot average price and deviation from Rate of Return Parity. In the right hand panel the open circles represent the average price per period of the Red Asset, the closed triangles represent the average per period of the Blue Asset, and the solid line represents the risk neutral expected value of both assets. In the left hand panel the closed squares represent actual deviations from Rate of Return Parity, and the solid line represents zero deviation from Rate of Return Parity.

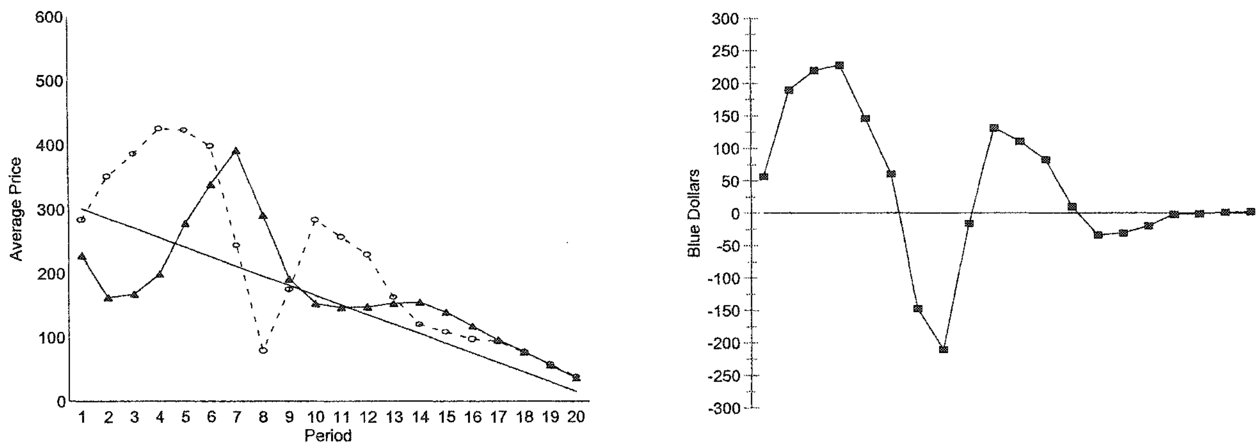

Figure 3.6. Random Action Weighted Average Trader average price and deviation from Rate of Return Parity. In the right hand panel the open circles represent the average price per period of the Red Asset, the closed triangles represent the average per period of the Blue Asset, and the solid line represents the risk neutral expected value of both assets. In the left hand panel the closed squares represent actual deviations from Rate of Return Parity, and the solid line represents zero deviation from Rate of Return Parity.

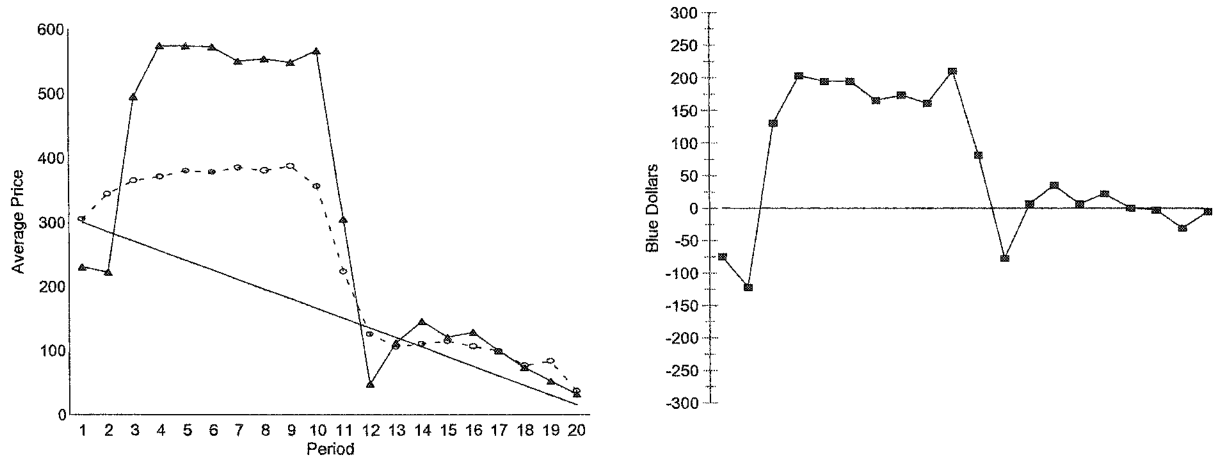

Figure 3.7. Profit Maximizing Weighted Average Trader average price and deviation from Rate of Return Parity. In the right hand panel the open circles represent the average price per period of the Red Asset, the closed triangles represent the average per period of the Blue Asset, and the solid line represents the risk neutral expected value of both assets. In the left hand panel the closed squares represent actual deviations from Rate of Return Parity, and the solid line represents zero deviation from Rate of Return Parity.

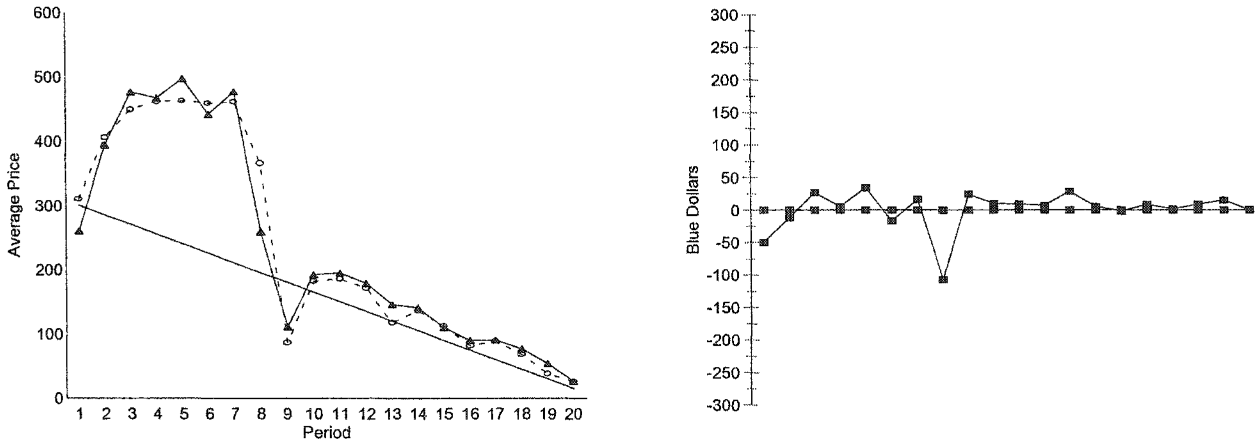

Figure 3.8. Random Action Weighted Average Traders with an Arbitrageur average price and deviation from Rate of Return Parity. In the right hand panel the open circles represent the average price per period of the Red Asset, the closed triangles represent the average per period of the Blue Asset, and the solid line represents the risk neutral expected value of both assets. In the left hand panel the closed squares represent actual deviations from Rate of Return Parity, and the solid line represents zero deviation from Rate of Return Parity.

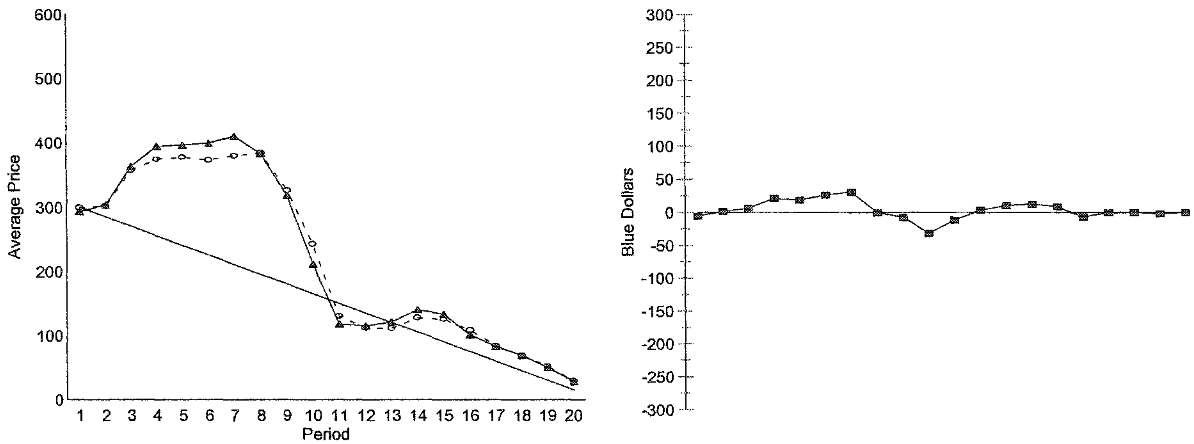

Figure 3.9. Profit Maximizing Weighted Average Traders with an Arbitrageur average price and deviation from Rate of Return Parity. In the right hand panel the open circles represent the average price per period of the Red Asset, the closed triangles represent the average per period of the Blue Asset, and the solid line represents the risk neutral expected value of both assets. In the left hand panel the closed squares represent actual deviations from Rate of Return Parity, and the solid line represents zero deviation from Rate of Return Parity.

Table 3.1. Risk Attitudes of Human Subjects

Subject Number	Session 1	Session 2	Session 3
1	1.01833	1.2104	0.7083
2	0.9375	1.4133	1.4225
3	1.2917	1.3246	0.5492
4	1.87567	0.83	0.8654
5	0.8521	0.76583	0.7677
6	0.8417	0.2523	0.9196
7	0.906	1.4483	1.3969
8	0.2967	1.4321	1.6015
9	1.3129	0.9554	0.4896
10	1.3501	0.4325	1.2819
Mean	1.0683	1.0065	1.0003
Standard Deviation	0.3975	0.4092	0.3748

Risk Attitudes are calculated as $RA = \frac{1}{n} \cdot \sum_{j=1}^{n} \frac{CE_j}{EV_j}$

Where n is the number of lotteries the subject participated in, CE is the certainty equivalent entered by the subject for lottery j, and EV is the risk neutral expected value of lottery j.

Table 3.2 Bubble Metrics of Human Populated Markets*

Session	Red Bubble Size	Red Bubble Duration	Blue Bubble Size	Blue Bubble Duration
1	19.2446	10	19.8538	9
2	3.7783	1	5.5989	2
3	9.1733	11	9.7182	11
Mean	10.7321	7.3333	11.72363	7.3333

* The size of the bubbles are calculated as

$$\beta = \Sigma_{t=1}^{20} \left| \frac{P_{n,t} - f_{n,t}}{f_{n,t}} \right|$$

where β represents the bubble metric, $P_{n,t}$ represents the price of asset n (Red or Blue) in period t (from 1 to 20), $f_{n,t}$ represents the risk neutral expected dividend value of the asset in period t.

Table 3.3 Mean Bubble Metrics for Robot Populated Markets*

Robot Type	Red Bubble Size	Red Bubble Duration	Blue Bubble Size	Blue Bubble Duration
ZITs	5.45	3	4.62	3
AERs	46.52	12	49.82	13
RAWATs	11.38	7.4	9.38	7.1
PMWATs	8.88	7.5	10.1	8.8
RAWATs with Arbitrageur	8.96	6.9	7.86	6.9
PMWATs with Arbitrageur	7.54	6.5	6.23	6.8

* The size of the bubbles are calculated as Equation

$$\beta = \Sigma_{t=1}^{20} \left| \frac{P_{n,t} - f_{n,t}}{f_{n,t}} \right|$$

where β represents the bubble metric, $P_{n,t}$ represents the price of asset n (Red or Blue) in period t (from 1 to 20), $f_{n,t}$ represents the risk neutral expected dividend value of the asset in period t.

Table 3.4. Exact Randomization Test p-values Comparing Robot to Human Populated Markets on Bubble Size and Duration

Robot Type	Red Bubble Size	Red Bubble Duration	Blue Bubble Size	Blue Bubble Duration
ZITs	0.0136	0.0139	0.0066	0.0088
AERs	0.0002	0.0017	0.0002	0.0011
RAWATs	0.996	0.9223	0.4274	0.9644
PMWATs	0.3167	0.8398	0.6675	0.5403
RAWAT-ARB	0.3526	0.9095	0.1023	0.8816
PMWAT-ARB	0.143	0.7485	0.0341	0.8677

Table 3.5. Median, Mean, and Standard of Deviation of RRP Prediction Errors For Human Traders*

	Raw			Absolute Value		
Session	Median	Mean	Standard Deviation	Median	Mean	Standard Deviation
1.1	1.837494	2.950714	25.32024	6.337494	16.06238	19.46022
1.2	0	8.617401	38.75281	9.670639	20.92165	33.45438
1.3	-3.96668	-2.07376	16.10739	10.31666	12.02804	10.527
Means	-0.70973	3.164785	26.72681	8.77493	16.33736	21.1472

* For each session a measure of bias is calculated for each period. This measure is $\beta_t = P_{B,t} - [E(D_{B,T-t+1})]/E(D_{R,T-t+1})]P_{R,t}$ and these terms are defined in Section III.

Table 3.6. Summary of RRP Prediction Errors for Human and Robot Market Populations

Population Type	(Mean of) Medians	(Mean of) Means	(Mean of) Standard Deviation
Human	-0.71	3.165	26.727
RAWATs	8.38	5.9845	112.754
PMWATs	24.9211	26.043	83.9124
RAWAT-ARB	-1.8989	-2.4581	46.9778
PMWAT-ARB	-1.1872	0.2727	22.6554

Table 3.7. Summary of Absolute RRP Prediction Errors*

Population Type	(Mean of) Medians	(Mean of) Means	(Mean of) Standard Deviation
Human	8.77493	16.33736	21.1472
RAWATs	71.389	94.2631	92.8755
PMWATs	57.403	73.2082	64.9794
RAWAT-ARB	16.1611	31.2281	36.4707
PMWAT-ARB	8.3535	15.314	18.4608

*For each session a measure of tightness is calculated for each period. This measure is the absolute value of $\beta_t = P_{B,t} - [E(D_{B,\,T-t+1})]/E(D_{R,T-t+1})]P_{R,t}$ and these terms are defined in Section III.

Table 3.8. Exact Randomization Tests Comparing Median RRP Prediction Error and Median Absolute RRP Prediction Error of Robot Populations to Human Populations

Robot Type	Bias p-value	Tightness p-value
RAWAT	0.7933	0
PMWAT	0.5696	0.0026
RAWAT-ARB	0.7999	0.0055
PMWAT-ARB	0.7562	0.7709

Appendix 3.1

Lottery Instructions

You are about to participate in an experiment in economic decision making. There are no correct or incorrect responses. The amount of money you will be paid at the end of the experiment will depend on the decisions you make. Funding for this experiment has been provided by the Social Sciences and Humanities Research Council of Canada.

This experiment will consist of 10 periods. At the beginning of each period you will be given a lottery ticket. A lottery ticket is the chance to win a prize with a given likelihood. The likelihood of winning the prize will vary from period to period and will be shown to you in the upper left corner of your screen as the probability. The size of the prize will be either 100 Lab Dollars or 200 Lab Dollars. This too will be shown to you in the upper left corner of your screen. At the end of the experiment your holdings of Lab Dollars will be converted into Canadian dollars at the rate of 1 Canadian Dollar for every 150 Lab Dollars you hold.

In each period you will have the opportunity to *sell* you lottery ticket to me. You will enter the *lowest* number of Lab Dollars for which would be willing to sell your lottery ticket for in the **selling price** box at the upper right hand side of your screen.

Once you have entered the *lowest* price for which you would be willing to sell your lottery ticket to me, press the button labelled **SELL TICKET**. The computer will then generate a random buying price between 1 and the prize. (So if the prize is 100 Lab Dollars, the highest possible buying price is 100 Lab Dollars) If the randomly generated buying price is higher than the selling price you entered, you will sell your lottery ticket to me for the randomly generated buying price. This amount will be immediately added to your Lab Dollar holdings, which is displayed at the bottom of your screen.

For example, if you entered a selling price of 25, and the computer randomly generated a buying price of 40, you would sell your lottery ticket to me for 40 Lab Dollars and the period would be over.

If the randomly generated buying price is lower than the selling price you entered, then you play the lottery. Remember the lottery is the chance to win the prize.

To start the lottery, press the button labelled **DRAW LOTTO**. This will cause the computer to generate another random number between 1 and 100. If the random number generated by the computer after you press the **DRAW LOTTO** button is lower than the probability shown in the upper left corner of your computer screen, you will receive the prize. If the random number is higher than the probability shown at the upper left corner of your screen, you will receive nothing.

For example, if the probability shown at the upper left of your computer screen was 50 and the random number generated was 45, then you would receive the prize. If the random number generated was 55, then you would receive nothing.

Once a period is over press the **START NEXT PERIOD** button to move onto the next period.

Are there any questions?

Appendix 3.2
Zero Intelligence Robots
Bubble Metrics

	Red		Blue	
Session	Bubble Size	Bubble Duration	Bubble Size	Bubble Duration
1	4.72	1	2.97	3
2	5.22	3	5.20	3
3	7.00	1	4.35	3
4	5.32	4	3.60	2
5	3.67	2	1.22	2
6	6.21	6	5.01	6
7	4.64	1	3.13	2
8	4.14	1	3.99	3
9	5.65	5	4.39	4
10	5.88	5	4.65	2
11	5.93	2	2.53	1
12	9.41	4	6.14	3
13	3.83	2	2.26	0
14	5.64	3	7.92	6
15	6.52	7	5.49	5
16	6.40	2	3.85	4
17	6.48	3	5.06	2
18	3.87	4	4.75	2
19	6.42	3	3.28	0
20	5.00	2	4.10	2
21	7.27	8	6.90	8
22	4.81	4	14.45	3
23	5.06	3	3.76	4
24	5.19	3	5.07	4
25	4.34	4	5.02	4
26	5.21	3	4.38	1
27	5.49	4	4.34	3
28	6.25	2	2.85	1
29	4.43	4	5.64	2
30	3.54	3	4.93	3
Means	5.45	3	4.62	3

Adaptive Expectations Robots
Bubble Metrics

	Red		Blue	
Session	Bubble Size	Bubble Duration	Bubble Size	Bubble Duration
1	43.92	12	49.84	13
2	46.80	12	50.37	13
3	50.09	13	57.96	15
4	49.63	13	58.23	15
5	42.26	11	46.41	12
6	44.42	12	50.34	13
7	50.87	13	51.06	13
8	45.57	12	57.68	15
9	49.02	13	44.74	12
10	39.34	11	57.98	15
11	46.02	12	55.34	14
12	46.74	12	52.90	14
13	49.69	13	41.40	11
14	50.11	13	52.42	14
15	48.74	13	47.08	12
16	45.67	10	54.30	14
17	50.99	13	51.25	13
18	45.75	12	56.02	14
19	43.98	12	42.58	12
20	43.57	12	53.16	14
21	43.61	12	42.30	11
22	38.91	11	51.15	13
23	50.40	13	34.67	10
24	49.62	13	48.84	13
25	48.72	13	56.28	14
26	45.81	12	55.95	14
27	46.41	12	46.43	12
28	47.78	13	35.86	10
29	46.88	12	48.48	13
30	44.30	12	43.53	12
Means	46.52	12	49.82	13

Random Choice Trend Based Robots
Bubble Metrics

	Red		Blue	
Session	Bubble Size	Bubble Duration	Bubble Size	Bubble Duration
1	9.38	11	9.48	6
2	21.29	11	12.52	8
3	29.54	15	10.92	6
4	8.11	6	6.83	7
5	7.60	6	5.25	8
6	12.29	8	5.44	2
7	11.02	3	22.00	8
8	9.64	5	15.51	13
9	6.57	6	11.31	9
10	8.67	7	7.89	10
11	5.29	3	5.95	5
12	5.29	3	5.95	5
13	24.40	12	6.18	5
14	11.66	6	8.33	11
15	12.79	11	10.33	7
16	14.97	10	6.01	5
17	12.54	7	4.94	4
18	15.34	8	4.93	2
19	5.04	4	16.28	8
20	7.90	4	4.65	2
21	8.34	4	10.60	8
22	10.24	9	6.90	4
23	9.05	2	6.12	6
24	18.95	15	20.29	12
25	10.92	11	9.05	11
26	10.23	12	8.13	10
27	7.76	4	5.33	4
28	8.93	9	9.11	9
29	4.98	3	8.04	5
30	12.53	8	17.05	12
Means	11.38	7.4	9.38	7.1

Profit Maximizing Trend Based Robots
Bubble Metrics

	Red		Blue	
Session	Bubble Size	Bubble Duration	Bubble Size	Bubble Duration
1	15.23046	9	7.477353	6
2	13.57026	12	6.150947	6
3	5.517783	4	4.033056	4
4	6.631082	6	5.329131	4
5	6.899132	4	25.39249	13
6	6.520239	5	11.64961	13
7	6.525442	4	21.81406	16
8	9.711879	8	7.729206	3
9	6.181261	5	9.208647	9
10	10.8297	11	9.109662	10
11	6.17791	5	4.446671	5
12	8.273478	5	4.884761	9
13	10.01134	11	30.47838	17
14	10.21483	9	5.418701	3
15	7.059469	7	25.23629	13
16	8.788917	9	3.388333	7
17	10.83391	8	4.572543	3
18	9.522743	9	10.77751	13
19	12.3689	12	17.33584	15
20	8.145572	7	4.245291	7
21	9.639573	11	5.918273	8
22	8.922215	7	7.263162	8
23	8.496579	6	9.077662	12
24	8.852332	5	11.81652	11
25	5.851934	6	4.824091	2
26	11.88874	12	12.97052	12
27	7.068707	5	9.008737	11
28	11.38912	9	5.044361	5
29	5.796585	4	7.673213	9
30	9.551897	11	9.267992	9
Means	8.88	7.5	10.1	8.8

Random Choice Trend Based Robots with Arbitrageur
Bubble Metrics

	Red		Blue	
Session	Bubble Size	Bubble Duration	Bubble Size	Bubble Duration
1	6.461251	3	5.430434	4
2	10.22557	10	13.84697	3
3	17.01423	12	10.57001	9
4	7.705724	7	8.252953	6
5	5.871699	3	8.367599	6
6	6.753466	5	14.26956	4
7	7.982894	6	5.95325	8
8	10.86633	7	4.417255	4
9	7.117282	5	3.481983	8
10	11.50097	13	6.516201	9
11	9.222664	6	3.612505	5
12	7.975502	6	6.860231	10
13	8.233763	8	9.7238	6
14	13.34611	11	9.021096	8
15	8.316757	7	9.189005	6
16	11.43853	7	8.37952	6
17	9.74421	8	9.613568	8
18	8.709845	11	8.801574	13
19	6.150653	4	5.527746	5
20	5.628716	1	5.309329	2
21	11.45056	8	9.247332	9
22	6.906111	4	5.404259	3
23	8.887999	8	6.747561	9
24	6.572976	5	5.023819	8
25	10.69586	9	8.074388	8
26	8.703971	7	8.249048	6
27	8.809221	9	8.405249	7
28	12.30433	8	14.15071	12
29	8.784883	5	8.69811	12
30	5.476182	5	4.606391	3
Means	8.96	6.9	7.86	6.9

Profit Maximizing Trend Based Robots With Arbitrageur
Bubble Metrics

	Red		Blue	
Session	Bubble Size	Bubble Duration	Bubble Size	Bubble Duration
1	9.17332	11	8.550117	12
2	8.692313	10	5.103335	8
3	5.24343	3	4.681102	5
4	9.011379	7	6.227043	8
5	5.74428	4	1.102814	4
6	7.823079	6	4.984389	6
7	6.453509	8	6.362702	7
8	7.251252	8	5.551501	10
9	7.705327	7	5.889817	8
10	7.932583	8	9.35982	9
11	4.741091	3	3.368658	4
12	8.808028	7	8.053826	6
13	8.808028	7	8.053826	6
14	6.772051	3	3.982498	3
15	6.570505	6	4.747779	7
16	7.657229	7	6.62431	9
17	6.93459	5	4.303888	7
18	6.44679	5	6.177587	5
19	9.216712	9	7.74791	9
20	11.09031	10	7.718215	10
21	6.056357	3	5.813722	2
22	10.26816	9	7.163198	11
23	5.509032	5	4.953431	4
24	4.951928	3	4.840014	3
25	6.767637	3	4.960212	3
26	9.357853	12	10.27227	12
27	7.543851	6	11.61419	9
28	9.75558	9	8.25464	9
29	5.660728	2	4.071366	1
30	8.388041	10	6.43963	7
Means	7.54	6.5	6.23	6.8

Appendix 3.3
Rate of Return Parity Prediction Errors

Median, Mean and Standard Deviation of Price Deviations from Rate of return parity, Weighted Average Trend Based Robots.

Session	Median	Mean	Standard Error
1	1.5	-27.4	88.17486
2	-13.16667	-72.005	217.1246
3	-141.5	-162.7607	242.6693
4	0	12.61667	103.9836
5	-8.75	-12.78583	99.39731
6	-6.75	-11.115	69.96659
7	-2.875	175.7017	324.2901
8	46.16666	100.6917	169.9591
9	27.75	44.245	100.0835
10	9.5	-0.2916668	63.1873
11	11.5	9.178332	27.81494
12	422.5	9.178332	27.81494
13	-143.25	-177.8042	195.4436
14	7	19.84167	100.5778
15	0.8333359	-15.01667	99.16895
16	-12.25	-16.025	80.40939
17	-19	-25.58917	57.07306
18	-53	-34.435	84.07563
19	9.75	133.0708	176.1283
20	-3.5	-8.171667	25.07613
21	22.5	78.27917	133.8313
22	-5.524994	-27.0422	75.95067
23	11.25	5.258333	64.55449
24	30.16666	76.25417	152.1348
25	-4.449997	7.413333	55.86521
26	-3	4.02750126	94.2213
27	10.75	-27.115	112.0797
28	6	38.50714	112.0249
29	13.75	16.44167	45.13622
30	37.5	66.38625	184.402
Means	8.38	5.9845	112.754

Median, Mean and Standard Deviation of Absolute Price Deviations from Rate of return parity, Weighted Average Trend Robots

Session	Median	Mean	Standard Error
1	46.75001	65.45	63.68609
2	90.5	156.3883	163.8785
3	218.5	228.1393	182.6127
4	57.625	78.225	67.37164
5	28	65.06917	74.85997
6	32.25	51.235	40.24041
7	103.9	246.3233	272.0019
8	98.5	146.7583	129.9497
9	63.81667	81.125	73.59362
10	27.33334	43.275	44.96037
11	22.925	24.13833	15.78039
12	422.5	318.8325	239.7835
13	151.4583	85.2958	175.7234
14	50.5	70.68333	72.60314
15	54	73.95834	65.55358
16	55.25	60.975	53.12584
17	35	48.2275	38.70783
18	83.66666	75.53166	48.07902
19	30.6666	139.0875	157.9294
20	16.5	19.27833	17.54674
21	35	98.9125	118.5848
22	30.5	55.70667	57.19779
23	28	45.45833	45.11807
24	94.66667	130.9792	105.8643
25	24	27.97	58.50124
26	39.125	69.13917	57.05181
27	35.25	71.185	89.52633
28	57.90475	84.72381	80.9599
29	33.33334	36.175	30.72993
30	74.25	129.6471	144.7418
Means	71.389	94.2631	92.8755

Median, Mean, and Standard Deviation of Price Deviations from Rate of return parity, Profit Maximizing Weighted Average Trend Robots

Session	Median	Mean	Standard Error
1	-32.7	-21.645	48.37127
2	-8	-66.8625	143.0027
3	1.5	-1.935001	28.33009
4	2.25	4.470239	17.73397
5	155	189.1093	208.0684
6	4.666668	63.08333	102.549
7	137.5	155.6458	162.1623
8	-13	-11.32917	29.96992
9	17	31.48833	59.83546
10	9.75	12.67333	39.51141
11	0.75	-5.683333	33.41642
12	-4.75	-10.01167	45.3395
13	191.25	166.27	167.2072
14	4.166668	17.47917	77.84746
15	219.25	173.510615	195.7685
16	-32.8666	-53.68666	97.441
17	-6.5	-26.64405	83.78001
18	25.5	66.61	103.9373
19	28.5	63.38334	106.6642
20	-7	-49.58167	84.78541
21	-24.75	-41.521	80.42133
22	27.38333	21.56333	55.55477
23	6.25	7.871666	109.7395
24	50	89.075	124.919
25	-11.25	-3.304167	25.2319
26	-11.5	-1.241667	65.35278
27	13.25	22.5325	61.72636
28	1	-16.64167	89.93671
29	9.233322	19.54	33.03376
30	-4.25	-12.9275	35.73281
Means	24.9211	26.043	83.9124

Median, Mean, and Standard Deviation of Absolute Price Deviations, Profit Maximizing Weighted Average Trend Robots.

Session	Median	Mean	Standard Error
1	45.5	45.645	25.23728
2	70.5	111.4625	109.8994
3	18.75	22.135	17.05256
4	11.29761	14.27976	10.99477
5	175.125	203.6657	193.0651
6	4.33334	81.08334	88.23108
7	137.5	175.4542	139.2583
8	19.1667	25.90417	18.082
9	31.75	48.82167	45.98887
10	26.5	31.49667	26.19094
11	22	24.74167	22.50086
12	26	35.16167	29.32176
13	191.25	181.38	149.7625
14	39.625	56.17917	55.31382
15	219.25	199.6395	167.5176
16	82.25	84.98666	70.18424
17	57.58333	62.63929	60.30066
18	60	92.41	80.52518
19	79.58334	94.76666	78.43948
20	53.41666	71.50167	66.29273
21	58.75	69	57.17435
22	39.5	49.44667	31.65638
23	27	71.955	81.59637
24	79.58334	119.2917	94.74831
25	16.25	18.80417	16.61125
26	29.75	44.14167	47.13354
27	28	46.60083	45.3723
28	36	62.70833	65.12168
29	21.5	28.04	25.79756
30	14.375	22.9025	30.01032
Means	57.403	73.2082	64.9794

Median, Mean, and Standard Deviation of Price Deviations from Rate of return parity, Weighted Average Trend Robots with a Single Arbitrageur

Session	Median	Mean	Standard Error
1	-2.75	3.834999	39.17933
2	-8.658325	-21.81166	118.0098
3	-13.55833	-63.21	120.7257
4	6	12.17167	53.4075
5	11	9.779168	16.73203
6	-5.35714	-3.928214	49.3271
7	-2.5	1.320834	26.28391
8	-13.5	-5.7775	63.69557
9	-5.266663	-2.5025	17.07368
10	-10	-8.820834	36.8459
11	-11	-10.93869	42.03367
12	2.25	-0.1858337	48.24064
13	-1.541672	-2.983335	23.92191
14	-11	6.323094	66.33228
15	4.583328	1.3375	38.72982
16	1.25	4.340237	66.48495
17	7.625	0.6241665	31.24636
18	6.875	3.633333	20.48101
19	-1.25	-0.8013878	20.64277
20	5.91666	13.5375	34.72284
21	6	9.07619	35.30493
22	-2.75	-10.4269122	24.14462
23	-8.25	-8.970833	25.51277
24	-1.5	3.979167	25.47404
25	-4.833328	-4.166667	43.70692
26	0.5	-25.88333	65.90038
27	0	-13.2625	50.84512
28	-3.25	49.23167	137.3588
29	3.75	5.075833	32.38366
30	-5.75	-14.3375	34.58556
Means	-1.8989	-2.4581	46.9778

Median, Mean, and Standard Deviation of Absolute Price Deviations from Rate of return parity, Weighted Average Trend Robots with a Single Arbitrageur.

Session	Median	Mean	Standard Error
1	15	27.87333	27.0682
2	17.25	67.31167	98.274
3	26.5	77.085	111.9181
4	15	33.845	42.45627
5	13.25	15.95417	10.61575
6	13.5	27.72821	40.49797
7	19.6666	21.09583	14.97408
8	24.5	42.76417	46.55359
9	11	12.86083	11.13537
10	19.5	27.9125	24.88793
11	22.25	32.73631	27.65343
12	13.5	31.0225	36.25118
13	13	18.175	15.29412
14	22.66667	46.10191	46.95538
15	17.16667	26.27917	27.83775
16	9.5	34.1669	56.66798
17	11	19.39917	24.09587
18	14.58333	16.43333	12.21064
19	9.5	14.50139	14.33325
20	14.25	24.5875	27.60837
21	19.25	25.33452	25.64238
22	9.25	17.03976	19.79318
23	16.3334	20.34583	17.31684
24	9.5	18.0375	17.9755
25	14.5	27.25	33.86629
26	26.41667	47.41667	51.78217
27	19.75	34.89583	38.58196
28	25.70834	87.01833	115.9656
29	10.875	19.17417	26.24544
30	10.6666	22.49583	29.66221
Means	16.1611	31.2281	36.4707

Median, Mean, and Standard Deviation of Price Deviations from Rate of return parity, Profit Maximizing Weighted Average Trend Robots with a Single Arbitrageur.

Session	Median	Mean	Standard Error
1	0.3500061	3.151667	14.16492
2	-1	5.4125	20.63487
3	-0.3333359	1.42	14.01335
4	-4.25	-10.29	33.50386
5	-2.25	-5.495833	17.40514
6	-11.46667	-9.438334	17.51075
7	-0.25	5.979167	24.71504
8	-4.666672	-6.191667	17.97824
9	1.5	7.508334	27.80653
10	4.25	9.824167	16.99987
11	-2.5	-11.09583	16.99987
12	-1.25	0.1524986	17.70253
13	-1.25	0.1524986	17.70253
14	0.25	1.611428	16.73199
15	1	0.5175003	8.601916
16	-2.5	0.0333328	17.6094
17	-5.75	-7.106666	17.73891
18	-1.75	-0.8958328	14.92327
19	1	5.229167	27.34099
20	-6	-15.13583	30.07499
21	1	-7.395833	23.48078
22	-5.5	-4.338334	21.52159
23	-1.5	-4.983334	18.31567
24	-2	-2.963096	14.08174
25	0	-0.9100006	19.25477
26	1.5	7.079167	23.94947
27	12.5	63.45762	113.3753
28	0	-2.308333	14.49554
29	-2.25	-6.181666	16.38052
30	-2.5	-8.616667	24.64645
Means	-1.1872	0.2727	22.6554

Median, Mean, and Standard Deviation of Absolute Price Deviations from Rate of return parity, Profit Maximizing Weighted Average Trend Robots with a Single Arbitrageur.

Session	Median	Mean	Standard Error
1	7.75	10.31833	9.951334
2	7	13.0125	16.68526
3	6	9.993334	9.663004
4	11	18.75	29.39888
5	11	13.5375	11.90896
6	16	15.905	11.58075
7	10.125	16.77083	18.77235
8	7.25	12.64167	13.97672
9	3.5	11.70833	26.23443
10	10.625	14.39917	13.12787
11	8.916664	20.5125	22.42754
12	5	10.2225	14.26199
13	5	10.2225	14.26199
14	6.214279	10.81143	12.63543
15	4	5.9675	6.06543
16	8.75	11.06667	9.193406
17	10.1666	14.65667	11.90411
18	8	10.14583	10.7328
19	9.75	18.3625	20.52767
20	13.35	21.80583	25.39952
21	10	15.97917	18.44321
22	8.5	14.53833	16.14011
23	6.125	11.23333	15.12532
24	4.75	9.363096	10.73573
25	6.5	13.09	13.82937
26	4	12.15417	21.69863
27	17	72.39571	107.5907
28	9.25	10.99167	9.410315
29	4.75	10.88167	13.56108
30	10.3333	17.98333	18.57905
Means	8.3535	15.314	18.4608

Chapter Four

Currency Crises in Experimental Asset Markets

Chapter Four
Currency Crises in Experimental Asset Markets

I. Introduction

A currency crisis is said to occur when a country's fixed exchange rate rapidly becomes no longer sustainable. This is in general due to large outflows of financial capital and/or speculative capital. In such an event the monetary authority of the country can not continue to defend the original fixed exchange rate and must therefore devalue the currency or allow the exchange rate to "float" (be determined solely be market forces). The currency crises in South East Asia in the latter part of the 1990s and in Argentina since the new millennium have renewed interest in the causes and effects of such events.

Competing models of currency crises have been proposed by many different researchers, each attempting to capture one or more aspects of currency crises. The explanations put forward thus far can be divided into two general categories. The first category, pioneered by Krugman [1979], is based on a discrepancy between the fixed exchange rate policy and other monetary policies. This is often referred to as a fundamentals-based model. In this type of currency-crisis model the country in question has had continued pressure to depreciate its exchange rate. This pressure is usually associated with a balance of payments deficit. This means that sooner or later the monetary authority will run out of reserves with which to defend the country's fixed exchange rate. At some point the value of the currency will have to be decreased. At the time of the currency crisis, individuals are simply buying up the monetary authority's foreign currency reserves in anticipation of the eventual collapse of the fixed exchange rate. Individuals will do this in anticipation of the increased value of foreign currency after the devaluation. In this situation it is not a question of whether or not a currency crisis will occur, but when it will occur. Prevention of crises such as these simply require consistent exchange rate and monetary policies.

In mid-December of 1997 the government of South Korea abandoned the previously fixed exchange rate for the Korean Won and requested assistance from the International Monetary Fund. Explaining this event using only the fundamentals-based model of currency crises is less than satisfactory to some researchers. Korea suffered neither chronic Current Account deficits nor an extremely overvalued exchange rate [Zalewski 1999]. Therefore, the strictly fundamentals-based model of currency crises seems unable to provide an explanation of this event. This is one example of why many feel that a different type of currency-crisis model is needed.

The second category of currency-crisis explanations can be described as self-fulfilling prophecy models. This type of model provides a "belief based" explanation. If individuals believe that a fixed exchange rate is no longer sustainable, then it will not be. Such beliefs will then result in a significant outflow of capital, placing great strain on the foreign currency reserves of the monetary authority. If such outflows continue, the monetary authority will have to devalue the currency or allow the exchange rate to float. As this explanation is based on beliefs of individual investors and speculators, the prescription of an appropriate preventative policy is much more difficult. Belief based explanations have gained in importance since the Asian Crises of the 1990's, although it is still unclear what role, if any, self-fulfilling prophecies play in currency crises.

The behavioural premise that underlies the self-fulfilling prophecy model is that a number of individuals are able to co-ordinate in an action which is not dictated by the fundamental value of a currency. In the environment of a currency crisis, this would mean co-ordinating in an attack on a country's currency that would exhaust its reserve and precipitate a devaluation even though the initial fixed exchange rate would otherwise be sustainable. Any policy prescription for a self-fulfilling prophecy model would require the manipulation of expectations of investors and speculators.

Given this dichotomy of crisis explanations and policy prescriptions it is essential to know which explanations and prescriptions are applicable. There has been no shortage of investigations into the observed currency crises of recent history [Berg and Pattillo 1999, Flood and Marion 2000, Jeanne and Mason 2000]. There are a number of problems with these studies which utilize field data. The first is that instances of currency crises are rare. There are only a small number of examples of currency crises in recent history. In the past 10 years the only recognised currency crises occurred in Mexico, Indonesia, Malaysia, the Philippines, South Korea, Thailand, and more recently Argentina. This shortage of data makes identifying the appropriate explanations difficult.

The second major difficulty in using field data is the number of variables that may be important to explaining a currency crisis. Exchange rates in general are poorly understood. A large number of variables have been identified as potentially central to the determination of an exchange rate at any point in time. Combine the number of potentially influential variables in determining the market exchange rate with the difficulty of acquiring accurate data on a number of these variables, and the problem becomes almost insurmountable.

A third difficulty lies in identifying instances in which a currency crisis might have arisen but did not. This inability to conduct counterfactual studies makes the problem even worse. Without counterfactual data it is almost impossible to differentiate between those variables at the root of a crisis and those that are the effect of a crisis or an impending crisis. In the absence of counterfactual data it is virtually impossible to identify cause and effect. For example under the fundamentals-based explanations the size of the reserve has no impact on whether or not a crisis will occur, only on the timing of the crisis. The self-fulfilling prophecy explanation does allow for the size of the reserve to be one of the roots of the crisis. This begs the question, is an observed small amount of foreign currency reserves held by a central bank an effect of a crisis in progress, or is it a cause of a future crisis? The former would be the case in a fundamentals based crisis, the latter would be the case in a self-fulfilling prophecy based crisis.

Given that currency crises are relatively rare, the amount of available data is limited. As well the determinants of exchange rates and the events which trigger the outflow of capital that characterizes a currency crisis are not well understood. These hinder analyses with field data. Controlled laboratory markets provide an alternate data source from which the drawbacks stated above may be excluded. Implementing a controlled laboratory environment allows the researcher to vary the levels of different potentially relevant variables and the fundamental value of the currency with respect to the exchange rate can be controlled independently of one another. In keeping with the above example, the size of the reserves with which the fixed exchange is to be defended can be varied independently of all other variables. To this end a laboratory environment was created in which the potential for currency crisis was real but not guaranteed. The specific environment is described in Section II.

The central goals of the experimental investigation presented in this essay are twofold. The first goal is to determine what role if any the size of reserves with which a fixed exchange rate is defended plays in determining whether or not the currency enters a crisis. The second, but no less important goal is to demonstrate that experimental methods can be meaningfully applied to the issues of international finance in general and to currency crises in particular. In addition, this laboratory environment allows further consideration of the power of rate of return parity to predict relative asset prices in a ever more complex environments.

The results of the experiment presented in this essay are quite varied. First, the currency in question only experiences a crisis in half of the eight sessions conducted at the McMaster University Experimental Economics Laboratory. Second, the currency in question experiences a crisis in three of four sessions in which the initial reserves were set at the low level but only one of the four sessions in which initial reserves were set at the high level. This is an indication that the level of reserves may be an important determinant of a currency crisis. Third, rate of return parity survives in this environment when a currency crisis does not occur. These and more specific results are discussed below.

The remainder of this essay is organized as follows. Section II describes the laboratory environment employed and the experimental design. Section III discusses models of currency crises as they will be applied to the laboratory environment described in Section II and makes predictions based on them. Section IV describes the results of the experiment. Finally, Section V concludes.

II. Laboratory Environment and Experimental Design

A. Introduction

The laboratory environment used in this study is an extension of the one used in Chapter Two to investigate rate of return parity in simultaneous asset markets. The laboratory environment is described by the nature of the asset markets, the nature of the assets themselves, the behaviour of the exchange rate that links the currencies in which the asset markets are denominated, the induced demand for Blue Dollars, and the endowments of subjects. Each of these factors will be discussed in turn.

B. The Asset Markets

International capital markets are set up as double auction markets, therefore the asset markets in this experiment are double auction markets. A market for Blue Assets denominated in Blue Dollars, and a market for Red Assets denominated in Red Dollars are conducted simultaneously. Each subject has the ability to act as a trader of assets in each of the two asset markets. A copy of the screen used by subjects can be seen in Appendix 4.1. Instructions were distributed to each subject and then read aloud at the beginning of each session. See Appendix 4.1 for a copy of these instructions. Each session consisted of 15 three minute trading periods. At the beginning of every session each subject received an endowment. Endowments consisted of some combination of Red Assets, Blue Assets, Red Dollars, and Blue Dollars. Having received their initial endowments, subjects' inventories of currency and assets were carried over from period to period. This meant that the supply of assets was held constant while the supply of currencies was increased each period by the amount paid to traders as dividends. At the end of each session, subjects' holdings of Red Dollars (R$) were converted into Blue Dollars (B$) at the exchange rate of the last period. Subjects' holdings of Blue Dollars were then converted into Canadian Dollars at a conversion rate of 1 Canadian Dollar for every 77 Blue Dollars.

C. The Nature of the Assets

The assets in this experiment were multi-period assets with randomly determined dividends. The dividends of these assets were determined by separate six-sided dice rolled by the subjects for each asset. A roll of a 1, 2, or 3 paid a dividend of R$10(B$10). A roll of a 4, 5, or 6 paid a dividend of R$20(B$20). The results of the rolls along with the corresponding dividends were recorded on a chalk board at the front of the laboratory in appropriately coloured chalk. Note that in any one period the Red and Blue Assets could pay different dividends., The expected values of the dividends from each asset, however, were the same magnitude (15).

D. Exchange Rate Behaviour

In this experiment the exchange rate was initially fixed at one Red Dollar to one Blue Dollar. There was a limited reserve of Red Dollars held by a "central bank" to support this exchange rate. Once the reserves were exhausted the exchange rate fell to one Red Dollar to two Blue Dollars. This recreates the possibility of currency crisis in this environment. The specific size of the reserve is discussed below in more detail in experimental design. If a currency crisis occurs, the exchange rate will remain at its new value throughout the session regardless of the behaviour of subjects.

E. Demand for Blue Dollars (Citizenship of Subjects)

In order to induce a demand in this environment for Blue Dollars that was theoretically greater than zero, a restriction on how individuals could divide their holdings was introduced. If subjects placed any positive probability on devaluation, the expected value of Red Dollars will exceed the expected value of Blue Dollars and Red Dollars will therefore be a dominant store of value. This is explained in more detail in Section III below. Specifically, the restriction was that any individual holding less than B$200 incurred a cost. The cost was 1/100 of a Canadian Cent per Blue Dollar below B$200 per second. This is cost intended to be similar to a transactions demand for money. Not holding a sufficient amount of local currency would mean that individuals would have to forego the utility of consuming local products. Through the restriction on

Blue Dollar holdings, and paying subjects based on the Blue Dollar value of their final holdings, subjects were effectively made citizens of the Blue Country.

F. Endowments of Subjects.

In this experiment subjects were randomly assigned to one of two endowment groups. The endowments of each endowment group contained some combination of Blue Dollars, Red Dollars, Blue Assets, and Red Assets. These endowment groups were the same in both treatments of the experiment. The specific endowments use are described in Table 4.1. As can be seen in the bottom row of Table 4.1, the total endowment of Blue Assets to all subjects is 20, and the total endowment of Blue Dollars to subjects is B$4500

G. Experimental Design

The size of the reserves of Red Dollars backing the Blue currency and the initial fixed exchange rate was used as the treatment variables in this experiment. There are two treatments. Initial reserves may be high or they may be low. The dividend structure of the two assets is identical. This permits traders to focus on the possibility of a crisis. Four sessions with high reserves and four with low reserves were conducted at the McMaster Experimental Economics Laboratory. The subjects were drawn from the undergraduate population of McMaster University in Hamilton, Ontario. All subjects who participated in this experiment had also participated in the experiment presented in Chapter Two. This subject pool was used to ensure that subjects were familiar with the basic environment of simultaneous double auction asset markets. Each session lasted approximated 1 hour and 30 minutes. The payouts to subjects ranged from $10 to $70 Canadian, including a $5 show up fee. Table 4.2 describes the central parameters of the experiment.

H. Exchange Rate Survey

Before each trading period subjects were asked to respond to the following question; "How likely do you think it is that the exchange rate will change in the next period?". Subjects responded by circling a number between 1 and 7 on a survey sheet that was collected before each period began. The number 1 was used to represent that the subject felt that it was almost impossible that the exchange rate would change in the next period. The number 7 was circled if subjects felt that the exchange would almost certainly change in the next period. The terms currency crisis and exchange rate collapse are not used in an effort to avoid framing problems. The surveys are not conducted after a crisis occurred. The goal of the survey is to identify the beliefs of all agents in each period. Thus the influence of beliefs on the possibility of a currency crisis and on rate of return parity can be considered.

III. Description of Hypotheses To Be Tested

In this environment a currency crisis is possible but not guaranteed. There are no external factors to cause a crisis. In effect the initial balance of payments of the Blue country is zero. Thus the fundamentals model of currency crises does not readily apply. The environment does, however, provide an ideal environment for demonstrating that self-fulfilling prophecies can cause currency crises. The application of a self-fulfilling prophecy model to the experimental environment will proceed in two stages. The first stage is to demonstrate that a self-fulfilling prophecy based crisis requires a high degree of co-ordination in the actions of traders. The second stage is to demonstrate the influence of the subjective probability of a currency crisis on the value of holding the potentially devalued currency, and thus the potential dynamics of the situation.

The co-ordination aspect of the self-fulfilling prophecy model is clearly laid out in Obstfeld [1998]. In this work a self-fulfilling prophecy model is described as a series of 2-by-2, two player, simultaneous decision games. The key feature of this model is the relationship between the reserves of the central bank dedicated to defending the fixed exchange rate and the amount of domestic currency that individual currency traders are able to bring to bear, referred to as "firepower". The term "firepower" is used to describe the amount of highly mobile capital a trader can transfer out of the country whose fixed exchange rate is threatened. In the laboratory environment described in Section II, this would be a subject's holdings of Blue Dollars. In each of Obstfeld's games, the traders must pay a transactions cost to sell their holdings of the currency in question. This feature is not directly incorporated in the laboratory environment described in Section II.

Obstfeld's 2-by-2, two player, games capture the principle that underlies the issue of self-fulfilling currency crises. In the game in which neither trader had sufficient "fire power" to exhaust the central bank's reserve alone, there remains the possibility that both individuals could profit by causing a currency crisis. The problem from either trader's point of view is that acting alone is costly. This brings about the question of how individuals will co-ordinate on either equilibrium.

The experimental environment created for this paper presents a slight modification of the games presented by Obstfeld. To capture this environment in the simplest manner possible a third action must be added for both players. The choice of actions is now, Hold, Sell Blue Dollars until holdings of Blue Dollars is equal to B$ 200, and finally Sell Blue Dollars until holdings of Blue Dollars equals 0. Consider the resulting 3-by-3 two player game in Table 4.3.

In Table 4.3 S is the number of seconds between sale of Blue Dollars and exchange rate collapse[14], and c is the conversion rate between $B and Canadian Dollars. The payoffs in Table 4.3 are as seen from any period of time in the game in which no single player independently has sufficient resources to bring about a currency crisis, while the two together have sufficient resources. The game presented in Table 4.3 is a simplification (3-by-3, two player) instead of the full strategy choice, 10 player game. The simplification does, however, capture the basic essence of the situation.

This formulation of the game involves no transactions costs. When players transfer Blue Dollars out of the economy they neither incur costs (unless they reduce

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[14] It should be noted that there is no motivation for a trader to hold less than B$200 after an exchange rate collapse has occurred. The motivation for holding less than B$200 is to maximize the value of holdings in the expectation that an exchange rate collapse will occur.

their holdings of Blue Dollars below B$ 200), nor do they enjoy any benefits unless there is a currency crisis. The negative entries in Table 4.3 corresponding to the action B$ 0 for either player represents the transactions demand penalty that traders incur by holding less than B$ 200. Finally the positive term (600c) corresponding to (B$ 0, B$ 0) represents the increase in the Canadian Dollar value of traders' firepower due to a currency crisis. The time component of the payoffs in Table 4.3 are representative of the nature of the induced transactions demand in the laboratory environment. In this particular laboratory environment a penalty is incurred for every second that the subject's holdings of Blue Dollars are less than B$ 200.

In this game, reserves are B$ 1200 and firepower is B$ 600 for each trader. Neither player has sufficient resources (B$ 600 each) to bring about the collapse of the exchange rate on their own. As the reserves in this example are equal to the total of the combined firepower the only way that the exchange rate can be made to collapse is if both traders choose to hold B$ 0. This particular version of this game has three symmetric equilibria: (Hold, Hold) , (B$ 200, B$ 200) , and (B$ 0, B$ 0) and two asymmetric equilibria. Once again players are faced with a co-ordination problem. Provided (0.02S) < 600 c[15], (B$ 0, B$ 0) is payoff dominant. Other equilibria in which no attack occurs are possible, however.

Co-ordination games have been studied extensively in laboratory experiments

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[15] This condition can also be expressed as 600 < 1.54S, which indicates that B$ 0 is payoff dominant when S < 390. Therefore in this case (when an individual holds B$600 and reserves are R$1200) it pays to eliminate holdings of Blue Dollars within 390 seconds prior to a currency crisis.

(see Ochs [1995] for a survey). While there are many interesting lessons to be learned from the simple 2-by-2 representation of the problem, the issue involves more than 2 players in naturally occurring currency markets as well as in the laboratory environment presented in Section II. Specifically, in this laboratory environment there are 10 individuals who may co-ordinate entirely (all 10 behaving in a manner consistent with some equilibrium) or partially (only some individuals behaving in a manner consistent with a given equilibrium). If at any time a sufficient number of individuals co-ordinate on reducing their holdings of Blue Dollars, the exchange rate between the two currencies will collapse. The proportion of individuals in the group who must co-ordinate on reducing their holdings of Blue Dollars in order to cause a currency crisis declines as the reserves with which the fixed exchange rate is defended declines. Initially in Treatment 1, 100% of individuals must co-ordinate on holding zero Blue Dollars in order to cause a crisis. Initially in Treatment 2, only 50% individuals must co-ordinate on holding zero Blue Dollars to cause a crisis.

If one accepts the conjecture that co-ordination is easier to achieve among a smaller proportion of individuals (Isaac and Walker 1988), it follows that currency crises will be more likely when reserves are lower. Thus, currency crises will be more likely in Treatment 2 (low initial reserves) than in the Treatment 1(high initial reserves). This forms the basis of the first alternate hypothesis.[16]

Alternate Hypothesis 1: Currency crises will occur more often when reserves are low

[16] Alternate hypotheses will be described throughout the chapter. The null hypotheses in each case will be that there is no treatment effect.

than when reserves are high.

The situation described as a simultaneous game above is static. The environment that subjects face is of course dynamic. In the experimental environment neither the "firepower" of subjects nor reserves are necessarily constant. The "firepower" of subjects will increase as dividends are paid to those subjects who hold Blue assets. Thus, considering the potential for changes in the level of "firepower" from the initial values, a currency crisis will become more likely as the experiment progresses. Again if one accepts the conjecture that co-ordination is easier to achieve among a smaller proportion of individuals, a second alternate hypothesis should be considered.

Alternate Hypothesis 2: A currency crisis will occur sooner when reserves are low than when reserves are high.

There is also the possibility that the level of reserves will change as the experiment progresses through continued small conversions of Blue Dollars into Red Dollars. The clearest way to explain some of the expected dynamics of the situation is consider the value of holding the Blue currency.

There are three potential reasons for subjects to hold Blue currency. The first is to avoid the penalty incurred by holding less than B$200, this is the experimentally imposed transactions demand. The second motive for holding Blue currency is a transactions demand based on a desire to participate in the Blue asset market. Given that no bid can be entered by a subject that is greater than the individual's holding of Blue dollars, any bid greater than B$200 must be covered by holdings of Blue Dollars greater than 200. Any bid less than B$200 could potentially be covered out of the imposed transactions demand, and any short fall in Blue Dollar holdings (below B$200) after a successful bid could be covered by the conversion of Red Dollars into Blue dollars. This strategy is not without cost, however. Recall, that any shortfall in holdings of Blue dollars (B$<200) will incur a penalty of 2 cents Canadian per second of the short fall. The third potential motivation for subjects to hold Blue currency is as a store of value.

The first two motivations above provide for a positive demand for the Blue currency. Equation 4.1 represents the demand for Blue currency based on these factors

$$D(B\$) = \max(200, \tau) \tag{4.1}$$

Where 200 is the transactions demand imposed in the experimental design and τ represents the transactions demand based on the desire to bid in the Blue asset market. Thus τ will be a function of the price of the Blue asset.

It is interesting to note that if prices in the Blue asset market are the risk neutral expected value of the stream of dividends, assuming zero probability of a currency crisis, there are only two periods in which tau will greater than B$200.[17] Ex ante it is not immediately obvious, however, that Blue asset prices will in fact reflect the risk neutral expected value of dividends. This type of pricing behaviour was not generally observed by this subject pool in Chapter Two. If there are price bubbles of a similar nature in this experiment, it indicates that τ will initially rise and then fall to or below two hundred

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[17] In the first period the risk neutral expected value of dividends assuming zero probability of a currency crisis is 15(15)=225. In the second period it is 15(14)=210. In the third period it is 15(13)=195. Thus by period 3 subjects can bid up to and including the risk neutral expected dividend value of the asset without having to hold Blue Dollars over the experimentally imposed transactions demand.

only in later periods. Smith, Suchanek, and Williams [1988] do, however, observe that price bubbles are less frequent and of smaller magnitude when traders are experienced. Thus it is possible that transactions demand for Blue currency based on a desire to participate in the Blue asset market will be less than B$200 as early as period 3 based on risk neutral expected value pricing.

The other possible motive for subjects to hold Blue currency in this environment is as a store of value. To examine how subjects will choose to hold their wealth until the end of the experiment, consider the value of each currency to a subject at the end of the session. As described in Section II, subjects' payments were based on the value of their holdings of Blue Dollars at the end of the session. The conversion rate between Blue Dollars and Canadian Dollars was constant at $1 Canadian to every B$77 and known by the subjects. Thus the expected value of Blue Dollars to subjects is;

$$E(V_C(B\$)) = \tfrac{B\$}{77} \tag{4.2}$$

Where $E(V_C(B\$))$ is the expected value of Blue Dollars in Canadian Dollars, B$ is the subject's holdings of Blue Dollars and 77 represents the conversion rate between Blue Dollars and Canadian Dollars. In considering the expected Canadian Dollar value of Red Dollars, one must take the two possible exchange rates between Red and Blue Dollars into account. The initial exchange rate between Red Dollars and Blue Dollars is R$1 = B$1, while the post currency crisis exchange rate is R$1 = B$2. Thus the Canadian Dollar value of Red Dollars can be expressed as

$$E(V_C(R\$)) = (1 - p) \cdot e_o \cdot \tfrac{R\$}{77} + p \cdot e_1 \cdot \tfrac{R\$}{77} \tag{4.3}$$

Where p is the subjective probability that a crisis will occur, e_0 is the value of the initial exchange rate between Blue and Red Dollars (1 in this laboratory environment), R$ is the subject's holding of Red Dollars, e_1 is the value of post crisis exchange rate between Blue and Red Dollars (2 in this case) and all other notation is identical to that of Equation (4.2).

Considering the values of the Red and Blue currencies from a strictly store of value perspective, it is clear that Blue currency will be a dominated means for storing value for any positive subjective probability of a currency crisis. Thus the only motive for purely rational subjects to hold Blue currency to cover transactions demand. This demand for Blue currency must be balanced against the weakness of the Blue currency as a store of value. This is the basis of alternate hypothesis 3.

Alternate Hypothesis 3: Traders will hold more than B$200 in each trading period.

Excess liquidity is defined as holdings of Blue currency in excess of the experimentally imposed transactions demand plus any transactions demand based on the desire to participate in the Blue asset market. The implication of this alternate hypothesis is that currency crises will occur earlier in sessions with low initial reserves than in sessions with high initial reserves. This provides additional support for alternate hypothesis 2.

Implicit in alternate hypothesis 3 are some other interesting points. The first is that the Blue currency holdings of individual subjects will be positively related to the price of the Blue asset. This is the basis of alternate hypothesis 4.

Alternate Hypothesis 4: The Blue Dollar holdings of subjects will be positively correlated with the price of the Blue asset.

Alternate hypothesis 4 leads to another interesting possibility. Given that price bubbles in both asset markets are observed in the experiments presented in Chapter Two, it seems somewhat likely that price bubbles will be observed in the Blue asset market in this experiment. If subjects only hold Blue Dollars in excess of B$200 in order to participate in the Blue asset market, the likelihood of a currency crisis will increase significantly after the collapse of the Blue asset price bubble. This leads to alternative hypothesis 5.

Alternative Hypothesis 5: Currency crises will not be positively related to the timing of a price bubble collapse.

The second stage of the analysis that was laid out in the introduction to this section describes a relationship between the subjective probability of a currency crisis occurring and individual holdings of Blue dollars. It has been shown that subjects will prefer to store wealth in Red dollars rather than in Blue dollars, all other things being equal. This preference for Red dollars as a store of value was mitigated by the desire to participate in the Blue asset market, which lead to a positive transactions demand. The expected cost of holding Blue dollars in order to participate the Blue asset market will be increasing in the subjective probability of a currency crisis occurring. This leads to alternative hypothesis 6.

Alternative Hypothesis 6: Individual holdings of Blue dollars will not be related to the subjective probability of a crisis occurring in the next period.

In much of the literature concerning currency crises it is implicitly or explicitly assumed that rate of return parity (interest rate parity in some form or another) holds. This is the basis of one of the common defensive prescriptions; the increase in the domestic interest rate. This approach will only work if one form or another of interest rate parity holds. This is the basis of alternate hypothesis 7.

Alternate Hypothesis 7: The price of the Blue asset in Blue dollars will not equal the price of the red asset in Red dollars adjusted by the prevailing exchange rate.

Alternate hypothesis 5 amounts to predicting that rate of return parity will not be observed between the Red and Blue assets. Rate of return parity will be computed and measured in exactly the same method as was employed in Chapter Two.

We will evaluate these seven alternate hypotheses against the corresponding alternative hypotheses using the data resulting from the eight market sessions described earlier in this chapter. Of particular interest will be the occurrence of currency crises, the individual holdings of Blue Dollars, and the relative prices of the Red and Blue assets.

IV. Results

The results may be summarized as follows. Currency crises do not occur in every session of the experiment. There were currency crises in only 1 of the 4 sessions of Treatment 1 (high initial reserves), and in 3 of the 4 sessions of Treatment 2 (low initial reserves). Currency crises occurred much earlier in the low initial reserves sessions than in the high initial reserves sessions. There appears to be little difference between Treatments 1 and 2 with respect to the accuracy of rate of return parity as a predictor of relative asset prices. There is a significant difference between rate of return parity as predictor of relative asset prices in sessions in which there was not a currency crisis and those sessions in which a currency crisis did occur. The results indicate that the level of reserves held by a central bank influences the likelihood of a currency crisis, while rate of return parity is a better predictor of relative asset prices in sessions in which a currency crisis does not occur. We now focus on each of the alternate hypotheses described in Section III.

Alternative hypothesis 1 is that there will be more crises when initial reserves are low than when initial reserves are high. Devaluation of Blue dollar occurred in only one session with high initial reserves (Treatment 1). When initial reserves were low (Treatment 2), three of fours sessions experienced devaluations. These results provide support for the rejection of Hypothesis 1. However, because of the small sample size, the t statistic for the difference between proportions is only 1.414. With six degrees of freedom, even on a one-tail test, the significance level exceeds 0.1 and we cannot reject the null hypothesis that the sample proportion 0.75 is not significantly different from the sample proportion 0.25. The same proportions from a sample twice the size used here would be significantly different.

Hypothesis 2 is that we would find no treatment effect on the timing of devaluations. When reserves are large, an average of 14.5 trading periods pass before there is either a devaluation or the session ends. With small reserves, an average of 9 periods pass. An exact randomization test of the difference in the length of time that passes before a devaluation by treatment indicates that we can reject the null hypothesis that the length of time that passes before a devaluation is not different when reserves are large or small ($p = 0.071$). The alternative hypothesis is that more time will pass before a devaluation when resrves are large than when they are small. Crises occur earlier when the initial level of reserves are low than when they are high.

Hypothesis 3 is that no subject will hold excess liquidity prior to an exchange rate collapse. Observation of the data for each session demonstrates that this was not the case. Table 4.4 shows the timing of the collapse and each subject's holding of Blue Dollars prior to the collapse. This table shows that not all subjects reduced their holdings of Blue Dollars to 0 prior to a collapse of the exchange rate, only 2 subjects out of 40 reduced their holdings of Blue Dollars to 0 immediately prior to an exchange rate collapse. There were 12 subjects who were holding B$200 or less at the time of a crisis, including those who reduced their holdings of Blue Dollars to zero. The majority of traders, 28 to be exact, were holding more than B$200 at the time of a crisis. Thus, there is little support for the prediction that subjects will not hold excess liquidity in Blue Dollars.

If one modifies the definition of excess liquidity to include a positive value for τ, it is possible for the results to be some what different. The subjects identified above as holding excess liquidity may actually be holding Blue currency in order to satisfy their desire to participate in the Blue asset market. Excess liquidity can be defined as

$$L_x = B\$^* - \max(200, \tau) \tag{4.5}$$

Where B$* is the number of Blue dollars actually held by a trader and max(200, τ) is the number of Blue dollars required to meet transactions demand as introduced in Equation

(4.1).

Still, a subject will only hold Blue Dollars in excess of B$200 if they require more than B$200 to cover their desired bid in the Blue asset market. The amount of Blue currency required to cover a bid in the Blue asset market will be related to the price of the Blue asset in that period. The simplest way to define τ is the average transaction price of the Blue asset in that period. Subjects will have little incentive hold more Blue dollars than the price of a single asset at a time, given that assets trade one at a time in the experimental environment. This strategy of course requires that a subject who is successful in acquiring a Blue asset must then transfer Red dollars into Blue dollars in order to attempt to acquire a second Blue asset.

In only one session is τ greater than B$200 at the time of a crisis. That session is session 2.4. In this session a currency crisis occurs at the 166th second of a 180 second period. At the time of the crisis half of the subjects were holding excess liquidity as defined by Equation (4.5) indicates. Again there is little support for the assertion that no subject will hold excess liquidity in Blue currency.

Hypothesis 4 was concerned with the correlation between the price of the Blue asset and each individual's holdings of Blue Dollars across periods prior to a currency crisis. The correlation coefficients for each individual subject are shown in Table 4.5. In general there does not appear to be a positive correlation between the value of Equation (4.1) and each individual's holdings of Blue Dollars prior to a currency crisis. Again this can be seen as an indication individual subjects are holding excess liquidity in Blue Dollars, contrary to the store of value properties of the currency.

It was further asserted, as alternative hypothesis 5, that a currency crisis would only occur after the collapse of a Blue price bubble, if any should exist. Surprisingly, this assertion receives some support from the timing of the currency crises and the collapse of price bubbles, in spite of the lack of consistent correlation between the value Equation (4.1) and the individual's holdings of Blue Dollars. This can be confirmed by observation of Figures 4.1 and 4.2 . In only one session of a possible four does the currency crisis occur before the apparent collapse of the Blue asset price bubble. That session is 2.4.

Hypothesis 6 is that individual's holdings of Blue dollars prior to a currency crisis will be negatively related to the subjective probability that a currency crisis will occur in the next trading period. Again, as the subjective probability of a currency crisis increases the expected cost of holding excess liquidity as Blue dollars increases. Thus subjects seeking to maximize their expected returns in the experiment will decrease their holdings of Blue dollars when their subjective probability of a currency crisis increases. To consider this hypothesis simple correlations of individual's holdings of Blue dollars with subjective probability of a crisis are shown in Table 4.6.

In Table 4.6 there are 25 subjects that exhibit a positive correlation between the subjective probability of a currency crisis and their holdings of Blue dollars. This indicates that these subjects actually increased their holdings of Blue dollars when they thought a currency crisis was more likely. Further there are 15 subjects that show no correlation between holdings of Blue dollars and the subjective probability of a crisis what so ever. These subjects gave the same response to the survey in all periods in which the survey was conducted. The remaining 40 subjects exhibited a negative correlation between the subjective probability of a currency crisis and their holdings of Blue dollars. Thus 50% of the subjects did behave in a manner consistent with the hypothesis of negative correlation, while 50% of the subjects in this experiment did not.

Hypothesis 7 concerns the applicability of rate of return parity to this environment. Figures 4.1 and 4.2 contain the per period average transaction prices in both markets for each session.[18] There are a number of methods that may be used to determine whether or not rate of return parity is observed. First and foremost consider the graphs in Figures 4.1 and 4.2. In observing the data in this format, it appears that rate of return parity is observed in at least four of the eight sessions. Specifically, by visually inspecting the data, it appears that rate of return parity holds for sessions 1.1, 1.3, 2.3, and 2.4. It is interesting to note that in only one of these sessions did the exchange rate collapse. Rate of return parity is rejected visually in session 2.1, while it is unclear to the eye whether or not rate of return parity holds in sessions 1.2, 1.4, and 2.2.

The visual inspection of the data in the left-hand panels of Figures 4.1 and 4.2 ignores the possibility that subjects beliefs concerning the possibility of a devaluation are influencing the price of the Blue asset. This possibility is taken into consideration in the right-hand panels of Figures 4.1 and 4.2 using the exchange rate risk surveys conducted before each period prior to an exchange rate collapse. The responses of subjects to the survey described in Section II are converted from categorical data to numeric data

[18] Average transaction prices are used to overcome a matching problem. If transactions do not occur at the same instant in time there is no exact match. If no transactions occur in a period the mid-point between the outstanding bid and ask is used as a proxy.

according to

$$p = -10 + 15 * Category \qquad (4.6)$$

This conversion method was selected for a number of reasons. The first is give a uniform distance between categories. The second is to ensure that the middle category corresponded to a 50% probability of exchange rate collapse. The third reason in to assign a low value to category 1 and a high value to category 7. Applying this conversion method means that a subject circling 1 was equivalent to a 5% probability of an exchange rate collapse occurring in the next period. If the subject circled 7 this was equivalent to 95% probability that the exchange rate would collapse in the next period. In those cases in which subjects circled 4 this was converted to a 50% probability of an exchange rate collapse in the next period.

The survey data was then averaged across all subjects in the session to estimate the average opinion of traders. Each individual's responses to the survey, along with average response is shown in Figures 4.3 and 4.4.

More than simply describing the data of individual subject's beliefs of whether or not there will be a currency crisis in the following period, Figure 4.3 and 4.4 indicate that there was little consistency of predictions among subjects. One notable exception is Session 1.1 in which subjects' beliefs converge on a prediction of very low probability of a currency crisis in the following period for the majority of the session. It is interesting to note that no currency crisis occurred in this session and that many subjects held excess liquidity in this session. For Sessions 2.1 and 2.2 there is an increase in the subjective likelihood of a currency crisis in the next period just prior to a currency crisis actually occurring. In these sessions it appears that many subjects did foresee the currency crisis before it occurred.

Returning to considerations of rate of return parity, the median, mean, standard deviation of the rate of return parity prediction errors in asset prices for each session are shown in Table 4.7. The data in Table 4.7 appear to indicate a positive bias in rate of return parity. No bias is described as no difference between the actual Blue asset price and the Blue asset price predicted by rate of return parity.

In order to test the results of visual inspection of the data, one must first consider whether or not the data can be pooled. To this end an exact randomization test was conducted on bias by Treatment. The exact randomization test returns a p-value of 0.214 indicating that the observations from both treatments can be pooled. A simple t-test using the mean bias in each session as the unit of observation indicates that one cannot reject the null hypothesis of no significant bias with a p-value of 0.2712.

Bias is not the only consideration for rate of return parity, however. The degree to which arbitrage opportunities are exploited is also important. The data on *tightness*, a measure of the extent to which arbitrage opportunities are exploited, defined as the absolute prediction error from the rate of return parity prediction, is presented in Table 4.8.

Using the data for session medians in Table 4.8 the degree to which arbitrage is complete can be compared between treatments, between sessions in which there was a currency crisis and those in which there was not, and finally to the Sessions of Treatment 1 of the experiment presented in Chapter Two. Session medians are used to minimize the effect of outliers in the data. Treatment 1 of the experiment presented in Chapter Two is chosen for the comparison as the characteristics of the two assets in this experiment are the same as those of Treatment 1 in Chapter Two, only the Chapter Two environment has unlimited reserves and so there is no chance of an exchange rate devaluation. The means of these data for eleven session are summarized in Table 4.9.

Exact randomization[19] tests are used to evaluate the effect reserves and the occurrence of a devaluation have on the ability of traders to exploit arbitrage opportunities in the eight sessions reported here. In addition, a comparison is made with comparable markets in which devaluation is not possible because of the unlimited reserves available to traders.

The mean of median measures of the effectiveness of arbitrage (tightness) for high reserve and low reserve environments are 31.950 and 25.502 respectively. The null hypothesis that these are different cannot be rejected against the alternative hypothesis that they are different (two-tailed test, p=0.628). For markets in which devaluation occur the mean tightness measure is 30.558 as compared to 26.894 for markets in which there is not a devaluation. The null hypothesis that the means of median tightness are not different in sessions in which a currency crisis occurred from session in which a currency crisis did occur can not be rejected by a Mann-Whitney U test (two tailed test, p =

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[19] Another means of examining rate of return parity exists but the data generated in these experimental sessions is not ideal for its application. With data sets of greater length it would be possible to test whether or not rate of return parity represents a co-integrating relationship between Red and Blue Asset price series. The greater length of data series is required due to the low power of Dickey-Fuller tests of stationarity with small sample sizes.

0.772)[20].

Finally, arbitrage is more complete when reserves are unlimited than when they are not. The sessions from Treatment 1 in Chapter Two have a mean tightness measure of 8.775. The null hypothesis that limiting reserves has no effect on the extent to which arbitrage opportunities are captured can be rejected against the alternative that limiting reserves has an effect (exact randomization test, one tail, $p = 0.006$). This alternative is based on the results in Chapter Two which demonstrated that exchange rate uncertainty affected the ability of traders to fully exploit arbitrage opportunities.

Overall, these results indicate that the possible occurrence of a currency crisis has a negative impact on the ability of traders to take advantage of arbitrage opportunities in simple simultaneous asset markets. The initial size of reserves, however, does not have this impact.

There are three central lessons to be gleaned from these results. The first is that currency crises based solely on the beliefs of traders are in fact possible. Second, the size of the reserves that a central bank dedicates to the defence of a fixed exchange rate do have an impact on the likelihood of a self-fulfilling crisis. The experimental results indicate that the higher the reserves dedicated to the defence of a fixed exchange rate the lower the probability of a crisis. Third, rate of return parity is a less accurate predictor of

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[20] Mann-Whitney U test is used in this case due a sampling issue with the exact randomization test. The exact randomization test is designed to test for treatment effects. The event of a currency crisis is not a treatment variable in this experiment making an exact randomization test inappropriate. A Mann-Whitney test, as described by the Stata 7 embedded help files, is to test the difference between two populations and is therefore more appropriate.

relative asset prices in the face of a currency crisis.

V. Conclusions

The experiment presented in this essay was designed to test the role of reserves in determining when and if a currency crisis driven by self-fulfilling prophecies would occur. In much of the existing literature it is unclear whether low foreign currency reserves of a central bank is a cause or an effect of a currency crisis. Determining which is in fact the case is essential for policy prescription.

There were a variety of predictions of how individual traders would behave in this environment and implications of such behaviour. These predictions were primarily focussed on the timing of a currency crisis, should such an event occur. The secondary focus of the experimental investigation was the applicability of rate of return parity to an environment in which the exchange rate between currencies was under the control of the traders.

The findings with respect to the influence of the reserves of the central bank are striking. Given that there were 3 times as many currency crises in sessions in which the reserves were low than there were when the reserves of the central bank were high, it appears that there is a negative relationship between the reserves of the central bank and the probability of a currency crisis. However, because of the small sample size, testing is unable to reject the null hypothesis of no difference in the likelihood of a crisis between treatments.

The timing of the crises, when such events did occur, lead one to the conclusion that the greater the reserves of the central bank, the long a currency crisis can be forestalled. There was a significant difference in the number of periods that elapsed prior to a currency crisis between the high reserve and low reserve treatments.

In spite of the results concerning the occurrence and timing of currency crises, there is at least one issue that remains unclear. That issue is the behaviour of individual subjects in the face of a potential currency crisis. A number of individuals did not behave in accordance with the fairly simplistic profit maximizing behavioural rules laid out in this paper. A number of individuals held excess liquidity in the potentially devalued currency, even at the time of a currency crisis. It is unclear at this time why an individual would choose to hold their wealth in such a manner.

The viability of rate of return parity in an environment in which there was the potential for a currency crisis has also been considered in this paper. The findings with respect to rate of return parity were mixed. In sessions in which there was no currency crisis, rate of return parity was found to be a fairly accurate predictor of relative asset prices. In sessions in which a currency crisis occurred, however, rate of return parity was not found to be an accurate predictor of relative asset prices.

Overall, the findings of this experiment indicate that there is a role of self-fulfilling prophecies in the occurrence and prediction of currency crises. Currency crises occurred in 50% of the sessions conducted, and yet there was no external motive for a currency crisis. In this essay, the size of the reserves dedicated to the defence of the fixed exchange rate by the central bank, was found to have some impact on the likelihood of a currency crisis. This finding was not found to be statistically significant, however. Given the findings concerning rate of return parity one of the common policy prescriptions for preventing a currency crisis, namely increasing the domestic interest rate, is called into question. If rate of return parity does not hold, an increase in the domestic interest rate will only serve to slow the domestic economy and not cause the needed capital inflow. As short any policy prescription for currency crises based on the assumption that rate of return parity holds should be treated with caution.

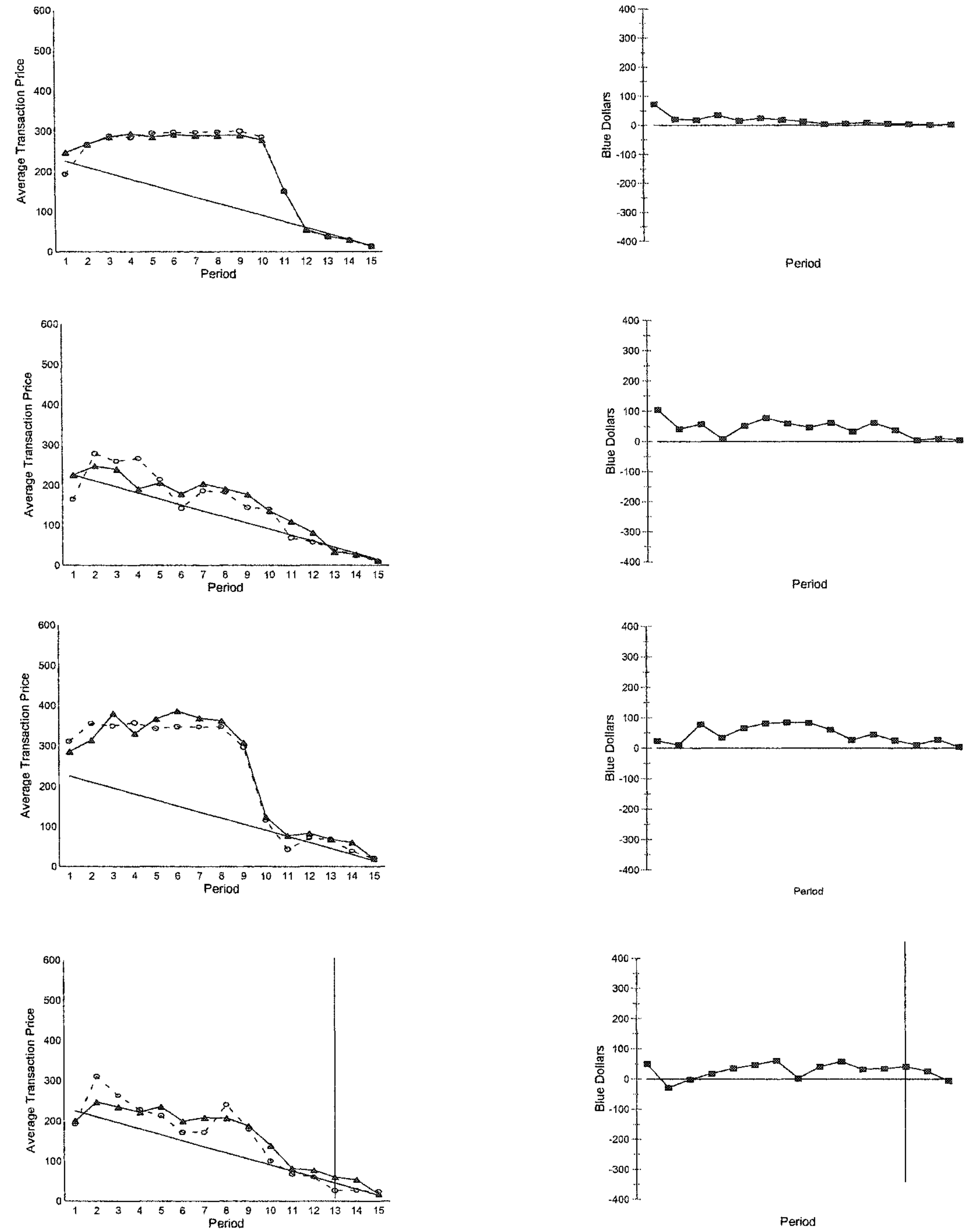


Figure 4.1. Treatment 1, Sessions 1.1, 1.2, 1.3, and 1.4 (Top to Bottom); Triangles are Blue Assets, Circles are Red Assets; Downward sloping lines in panels on the left identify fundamental asset values. Vertical lines indicate the period of a currency crisis. Right-hand panels display differences between observed Blue Asset prices and those predicted by rate of return parity.

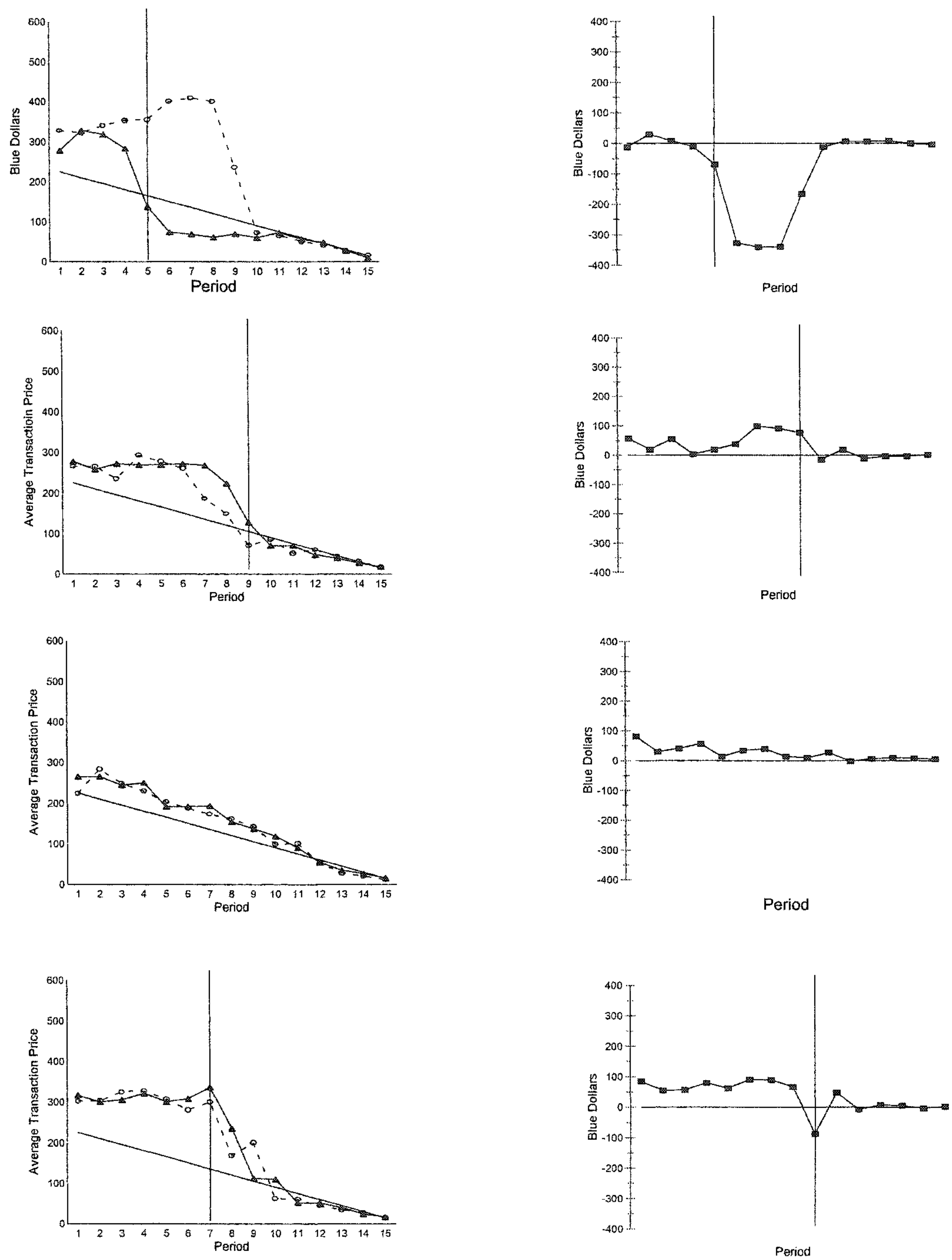


Figure 4.2. Treatment 2, Sessions 2.1, 2.2, 2.3, and 2.4 (Top to Bottom); Triangles are Blue Assets, Circles are Red Assets; Downward sloping lines in panels on the left identify fundamental asset values. Vertical lines indicate the period of a currency crisis. Right-hand panels display differences between observed Blue Asset Prices and those predicted by rate of return parity.

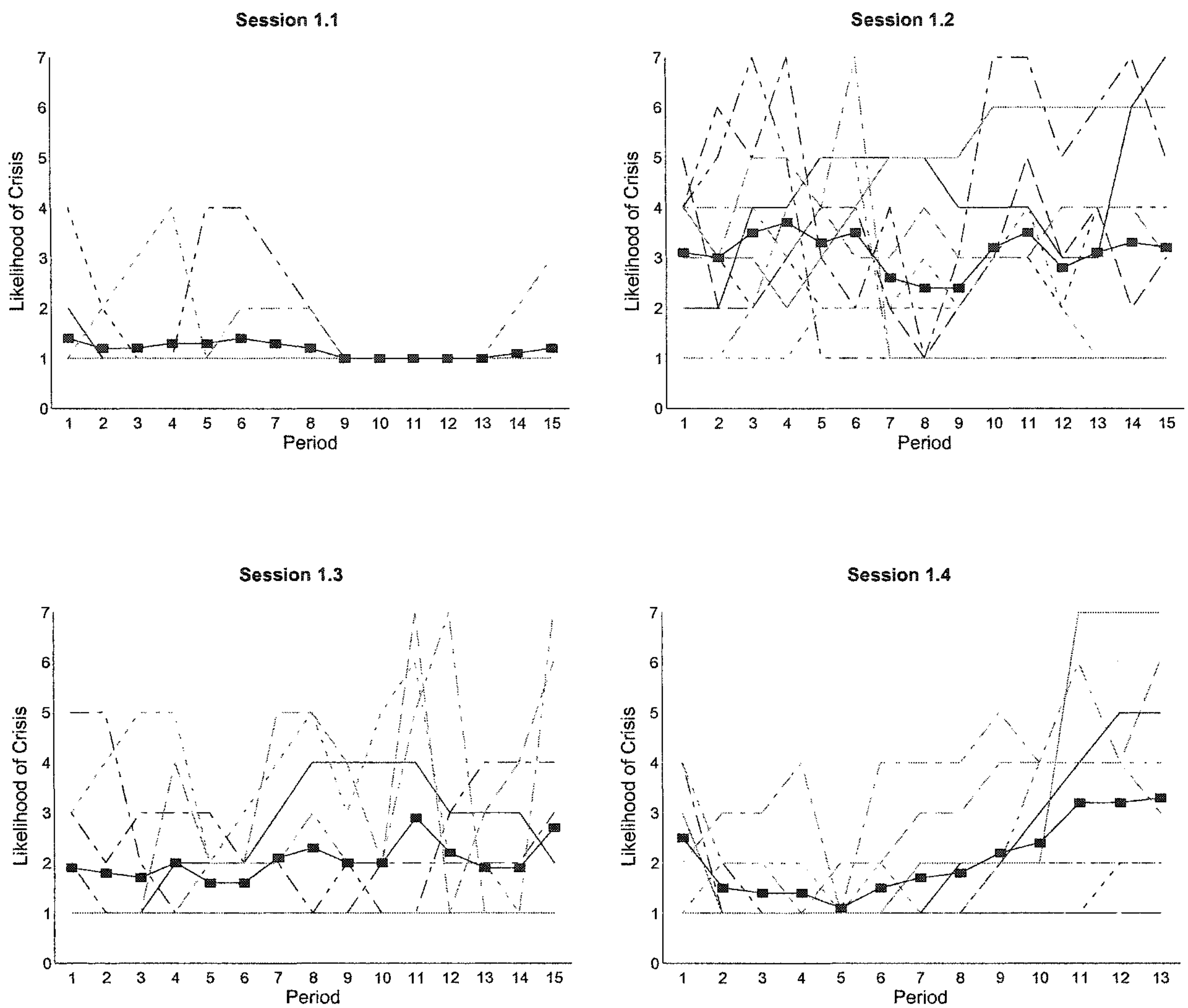


Fig 4.3. Treatment 1, time path of survey responses for each subject. Dark line in each panel indicates the average opinion.

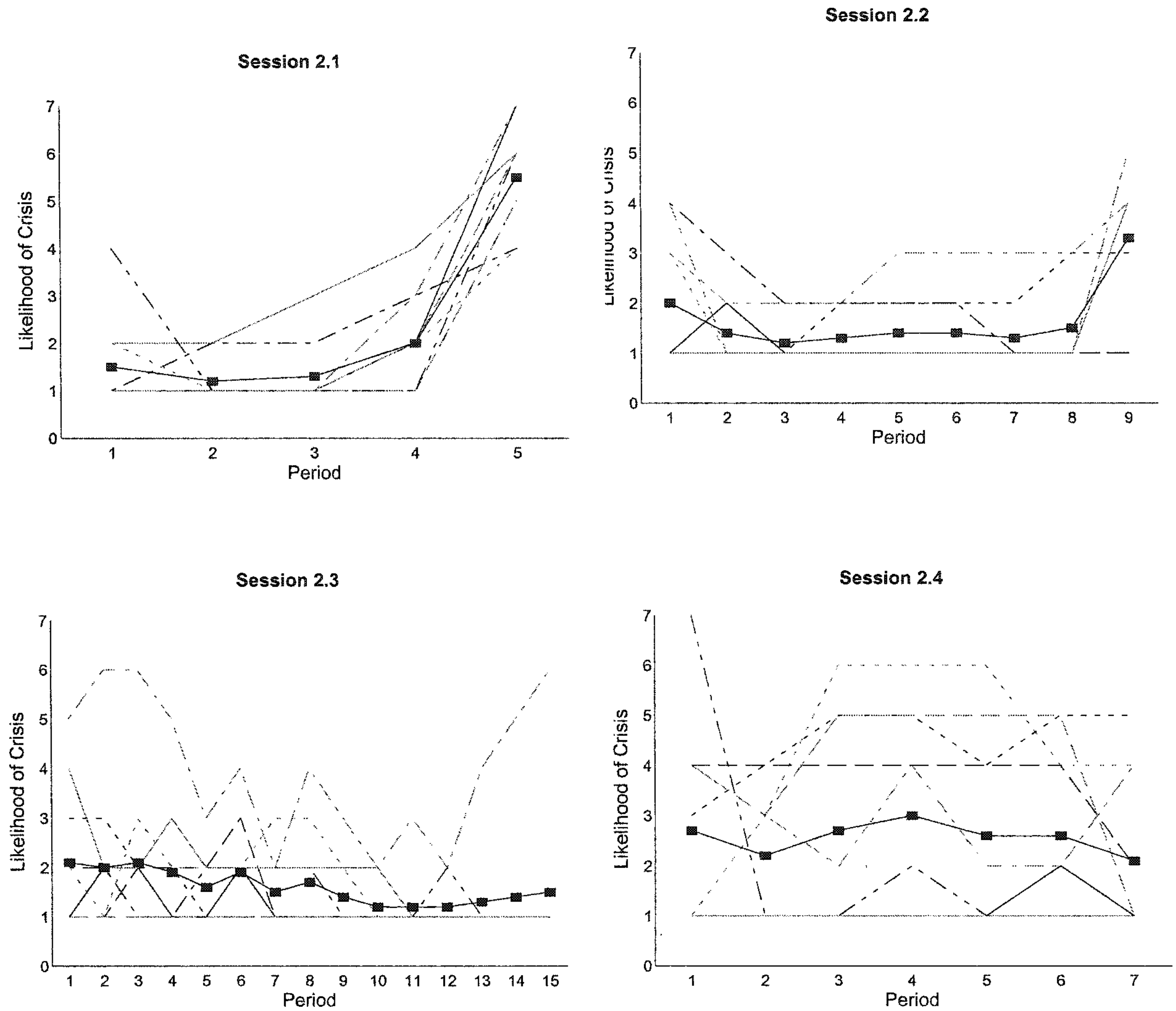


Fig 4.4. Treatment 2, time path of survey responses for each subject. Dark line in each panel represents the average opinion

Table 4.1. Endowments of Subjects,

Endowment Group	Number of Subjects	Red Assets	Blue Assets	Red Dollars	Blue Dollars
A	5	3	1	300	600
B	5	1	3	600	300
Total	10	20	20	4500	4500

Table 4.2 Experimental Design and Parameter Values

Initial Reserves	Number of Sessions	Red Dividends (Low, High)*	Blue Dividends (Low, High)*	Exchange Rate in Period t (Reserves >0, Reserves =0)
R$ 4500	4	-1020	(10, 20)	(R$1=B$1, R$1=B$2)
R$ 2500	4	(10, 20)	(10, 20)	(R$1=B$1, R$1=B$2)

* There is one chance in two that at the end of a trading period the Red dividend will be high. The same is true for the Blue dividend. The dividend outcomes are independent.

Table 4.3 Payoff Matrix for Two Players Holding B$600, Initial Reserves are R$1200*

		Trader 2		
		Hold	B$ 200	B$ 0
Trader 1	Hold	0, 0	0, 0	0, -0.02S
	B$ 200	0, 0	0, 0	0, -0.02S
	B$ 0	-0.02S, 0	-0.02S, 0	600c - 0.02S, 600c - 0.02S

* Payoffs are expressed as deviations from the (Hold, Hold) Strategy Pair. S denotes the number seconds during which an individual holds less than B$200. c is the conversion rate between Blue Dollars and Canadian Dollars, c = 1/77. The strategies Hold, B$200, B$0 are retain initial endowment of Blue Dollars, convert all excess liquidity (B$400) to Red Dollars, convert entire initial endowment (B$600) to Red Dollars, and incurring a penalty of 2 cents Canadian per second respectively.

Table 4.4 Individual Subject Holdings of Blue Dollars At Time of Crisis

		Subject Number									
Session *	Crisis Period	1	2	3	4	5	6	7	8	9	10
1.4	13	928	200	200	285	200	350	200	906	0	216
2.1	5	263	200	470	300	152	225	200	360	260	1020
2.2	9	402	344	413	240	400	915	1496	290	225	200
2.4	7	250	470	0	285	86	350	785	755	1059	200

*The designation x.y indicates Treatment x and session number y.

Table 4.5 Correlations of Blue Dollar Holdings to Equation 4.1

	Subject									
Session	1	2	3	4	5	6	7	8	9	10
1.1	-0.9	-0.3	-0.7	0.1	0.35	-0.4	0.19	-0.2	-0.7	-0.3
1.2	-0.6	-0.4	-0.6	-0.2	-0.5	-0.5	-0.8	-0.5	-0.4	-0.4
1.3	-0.7	-0.2	-0.5	-0.7	0.19	-0.5	0.2	-69	0.3	0.38
1.4	-0.4	0.79	-0.2	0	-0.4	-0.1	0	0	0.35	0.38
2.1	0.22	0.27	0	-0.4	0	0.54	0.44	0.27	0.19	0.25
2.2	-0.5	0.14	0	0.44	-0.8	-0.3	-0.1	0.1	0.26	0.15
2.3	0.32	-0.2	-0.1	-0.2	-0.2	-0.9	-0.9	-0.5	-0.8	-0.3
2.4	-0.7	0	-0.2	0.1	0.1	0.16	0.16	0	0.32	-0.1

Table 4.6 Correlations of Individual Subjects' Holdings of Blue Dollars With Subjective Probability of a Currency Crisis - Prior To A Crisis*

	Subject									
Session	1	2	3	4	5	6	7	8	9	10
1.1	0	0	-0.2	0	0.52	0	0	-0.7	-0.4	0.1
1.2	0	0.11	0.52	0.37	-0.5	0.74	-0.3	0.15	-0.6	-0.8
1.3	0.51	0	0	0.16	0.68	0	0	-0.7	-0.3	0
1.4	0.92	0	-0.3	-0.4	-0.6	0.73	-0.5	-0.3	-0.4	-0.7
2.1	-0.5	-0.6	-0.2	0.84	-0.2	-0.6	-0.2	-0.7	-0.6	0.65
2.2	0.38	0	0.26	0.69	-0.2	0.41	0.35	-0.2	-0.7	-0.5
2.3	-0.4	-0.5	-0.1	-0.2	-0.5	-0.4	0	0.11	-0.4	0
2.4	0.24	-0.7	0.57	0.22	-0.5	0	0.2	-0.4	0	0

* Entries of zero indicate that the subject always reported the same value for their subjective likelihood of a currency crisis in the next period, thus no meaningful correlation could be calculated. Correlations are only calculated when a currency crisis is possible.

Table 4.7. Median, Mean, and Standard Deviation of RRP Prediction Errors by Session (Bias)*

Session	Median	Mean	Standard Deviation	Bias =0 t-test p- value
1.1	13.537	16.301	17.78	0.0041
1.2	46.508	43.927	28.082	0
1.3	33.75	43.998	28.058	0
1.4	34.004	27.314	25.072	0.0011
2.1	-10.958	-81.857	134.606	0.0391
2.2	19.386	29.338	36.561	0.0095
2.3	13.779	24.433	21.985	0.001
2.4	54.195	36.349	47.93	0.132
Means	25.525	17.477	42.509	

* For each session a measure of bias is calculated for each period. This measure is $\beta_t = P_{B,t} - [E(D_{B,T-t+1})/E(D_{R,T-t+1})]P_{R,t}$ and these terms are defined in Section III.A.

Table 4.8. Median, Mean, and Standard Deviation of Absolute RRP Prediction Errors by Session (Tightness)*

Session	Median	Mean	Standard Deviation
1.1	13.537	16.301	18.404
1.2	46.508	43.927	29.067
1.3	33.75	43.998	29.043
1.4	34.004	32.225	18.979
Treatment Means	31.95	34.113	23.873
2.1	12.5	89.464	134.225
2.2	19.386	34.098	33.297
2.3	13.779	24.805	22.321
2.4	56.341	49.671	35.167
Treatment Means	25.502	49.502	56.253

* For each session a measure of tightness is calculated for each period. This measure is the absolute value of $\beta_t = P_{B,t} - [E(D_{B,\,T-t+1})]/E(D_{R,T-t+1})]P_{R,t}$ and these terms are defined in Section III.A.

Table 4.9 Mean Completeness of Arbitrage Measures (Median Absolute Prediction Errors per Session from Rate of Return Parity Price Predictions)*

	Devaluation Impossible	Devaluation Possible		Row Totals
Treatment		No Devaluation	Devaluation	
Unlimited Reserves	8.775 (3)			8.775 (3)
High Reserves		31.265 (3)	34.004 (1)	31.950 (4)
Low Reserves		13.779 (1)	29.409 (3)	25.502 (4)
Column Totals	8.775 (3)	26.894 (4)	30.558 (4)	23.285 (11)

* Number of observations in each cell are in parentheses. Smaller numbers indicate few arbitrage opportunities are missed.

Table 4.10. Individual Traders' Holdings of Blue Dollars - Pre and Post Crisis.

Session *	Reserves **	Subject									
		1	2	3	4	5	6	7	8	9	10
1.4(13)	1070	928	200	200	200	1045	349	200	956	0	392
1.4(14)	0	1009	200	200	325	3878	480	4456	1015	180	575
2.1(5)	168	263	200	470	300	220	225	300	360	260	1020
2.1(6)	0	293	200	1780	450	200	225	340	590	340	1030
2.2(9)	367	1009	344	353	240	200	1040	1496	290	225	220
2.2(10)	0	3756	524	603	109	3890	906	1536	440	225	325
2.4(7)	2206	289	670	570	285	1251	350	785	765	1231	260
2.4(8)	0	250	520	10	325	0	380	805	775	1869	230

* x.y - x indicates treatment number and y indicates session number. The number in brackets indicates the period in question. The first entry for a session indicates the end of the period prior to the crisis. The second entry for a session indicates the end of the period in which the crisis occurred.

** Reserves will be zero after a crisis occurs in all cases.

Appendix 4.1
Double Auction Asset Market Instructions

You are about to participate in an experiment in economic decision making. There are no correct or incorrect responses. Your decisions and the decisions of others will determine how much you are paid at the end of this session. You may earn a substantial amount of money. Funding for this experiment has been provided by the Arts Research Board.

Each of you will be able to act as an asset trader in this experiment. You will be able to buy and sell two different assets, Red Assets and Blue Assets, as you see fit in separate double auction markets. You can think of an asset as being shares in a company which will pay you some dividend every year. An asset gives you some income every time period, in this case every period.

There will be 15 trading periods in this session. Each trading period in this session will last for 3 minutes or 180 seconds. The time remaining in a trading period will be shown at the upper right hand corner of your computer screen. There will 2 different kinds of money in this environment; Red Dollars and Blue Dollars. Red Dollars are required to buy Red Assets and Blue Dollars are required to buy Blue Assets. At the end of the session your holdings of Red Dollars will be converted into Blue Dollars at the exchange rate shown in the last period. Then your total of Red Dollars will be converted into Canadian Dollars at an exchange rate of 1 Canadian Dollar for every 77 Blue Dollars.

At the beginning of the session you will receive an endowment. Your endowment will contain some combination of; Red Assets, Blue Assets, Red Dollars, and Blue Dollars. Not all individuals will receive the same endowment.

The return to holding a Red Asset at the end of a trading period will be a dividend of either R$10 or $R20, never any other value. The value of the dividend will be selected by the roll of a die at the end of each trading period. A roll of 1, 2, or 3 will mean a dividend of R$10. A roll of 4, 5, or 6 will mean a dividend of R$20. If you were to hold a Red Asset for a sufficiently long period of time the average return would be R$15 per period. The asset has no value to anyone other than the dividend received at the end of each period. After the dividend has been paid in the 20th period, the asset will not create any more income. All Red Assets are identical. Does everyone understand how the return to the Red Asset is determined?

The return to holding a Blue Asset at the end of a trading period will be a dividend of either B$10 or B$20, never any other value. The value of the dividend will be selected by the roll of a die at the end of each trading period. A roll of 1, 2, or 3 will mean a dividend of B$10. A roll of 4, 5, or 6 will mean a dividend of B$20. If you were to hold a Blue Asset for a sufficiently long period of time the average return would be B$15 per period. The asset has no value to anyone other than the dividend received at the end of each period. After the dividend has been paid in the 20th period, the asset will not create

any more income. All Blue Assets are identical. Does everyone understand how the return to the Blue Asset is determined?
The dividend of the Red Asset and the dividend of the Blue Asset are independent of each other. The dividend on the Red Asset has no impact on what the dividend of the Blue Asset will be. These dividends will be determined by separate rolls of the die.

Please fill in the following chart as the die is rolled. Someone will check your work.

Period	Roll	Red Dividend	Roll	Blue Dividend
1				
2				

The return to holding each type of asset will be revealed to each of you, along with your and only your total income of Red Dollars generated by holding Red Assets and your total income of Blue Dollars generated by holding Blue Assets on a separate screen between trading periods. The dividend to holding either type of asset is the same for all traders. For example, if you receive a dividend of R$20 for each Red Asset you hold, everyone else who holds Red Assets will also receive a dividend of R$20 on each asset.

<u>Bidding In Either Market</u> (to buy an Asset)

Entering a bid is asking all the other traders if one of them would like to give you an asset in exchange for the amount you bid. This is offering to buy an asset.

Note that you may not enter a bid in the Red Asset market that is higher than the total Red Dollars you hold nor may you enter a bid in the Blue Asset market that is higher than the total Blue Dollars you hold.

Whenever you enter a bid it is to buy <u>*ONE*</u> Asset.

<u>Asking in Either Market</u> (to sell an Asset)

Entering an Ask is the asking all the other traders if one of them would like to give you amount of Red or Blue Dollars (depending on which market you enter the ask in) in exchange for one of your Assets. This is offering to sell an Asset.

Note that you cannot enter an Ask in the Red Asset market if you do not own any Red Assets, nor can you enter an Ask in the Blue Asset market if you do not own any Blue Assets.

Whenever you enter an ask it is to sell <u>*ONE*</u> Asset.

<u>Accepting an Ask</u> (Purchasing an Asset)

When you want to ***purchase*** an Asset from the trader with the outstanding ask, you want to accept the Ask.

Note that you cannot accept a Red (Blue) ask more for more Red (Blue) Dollars than you have.

When an ask has been accepted, all traders will be informed that a transaction has taken place in the feedback area of their screens and the Last Trade Price will be updated with the price at which the transaction occurred.

Accepting a Bid (Selling an Asset)

When you want to ***sell*** a Red Asset to another trader you want to accept the outstanding bid.

Note that you cannot accept a Red (Blue) bid if you do not own any Red (Blue) assets.

When a bid has been accepted, all traders will be informed that a transaction has taken place in the feedback area of the their screens and the Last Trade Price will be updated with the price at which the transaction occurred.

EXCHANGING CURRENCY

Buying Red Dollars

Buying Red Dollars is the same as trading in your Blue Dollars for Red Dollars. This is the only way you can purchase Red Assets if you have no Red Dollars.

In order to buy Red Dollars simply use your computer mouse to press the button at the top of your computer screen labelled **BUY RED DOLLARS**. This will activate the currency exchange window. Use your keyboard to enter the number of Blue Dollars you would like to trade in for Red Dollars. The exchange window calculates how many Red Dollars you can buy with the number of Blue Dollars you entered in the exchange window. Adjust the number of Blue Dollars you wish to trade in until the exchange window shows the number of Red Dollars you wish to buy. To complete the transaction press the button labelled OK. Your holdings of Blue Dollars will be reduced by the amount shown in the exchange window and your holdings of Red Dollars will be increased by the amount shown in the exchange window.

Note that your purchase of Red Dollars is limited by the number of Blue Dollars you have and the rate at which Blue Dollars trade for Red Dollars.

BUYING BLUE DOLLARS

Buying Blue Dollars is the same as trading in your Red Dollars for Blue Dollars. This is the only way you can purchase Blue Assets if you have no Blue Dollars.

In order to buy Blue Dollars simply use your computer mouse to press the button at the top of your computer screen labelled **BUY BLUE DOLLARS**. This will activate the currency exchange window. Use your keyboard to enter the number of Red Dollars you would like to trade for Blue Dollars. The exchange window calculates how many Blue Dollars you can buy with the number of Red Dollars you entered. Change the number of Red Dollars you wish to trade until the exchange window shows the number of Blue Dollars you wish to buy. To complete the transaction press the button labelled OK. Your holdings of Red Dollars will be reduced by the amount shown in the exchange window and your holdings of Blue Dollars will be increased by the amount shown in the exchange window.

Note that your purchase of Blue Dollars is limited by the number of Red Dollars you have as well as the rate at which Red Dollars trade for Blue Dollars.

THE EXCHANGE RATE BETWEEN RED AND BLUE DOLLARS

At the beginning of this session the exchange rate will be B$1 = $R1. Also at the beginning of the session there will be a reserve of Red Dollars to guarantee this exchange rate. Every time a Blue Dollar is exchanged for a Red Dollar this reserve will fall by $R1. For example if you exchange B$50 for $R50 the reserve will fall by $R50. Every time a Red Dollar is exchanged for a Blue Dollar the reserve will increase by $R1. For example if you exchange $R50 for B$50 the reserve will increase by $R50.

The Reserves are displayed at the Top of your screen between Buy Red $ button and the Buy Blue $ button.

If the reserves ever fall to $R0, the exchange rate between Red Dollars and Blue Dollars will change for the remainder of the session. The new exchange rate will be $R1 = B$2. If the exchange rate does change this will always be the exchange rate including the end of the session when your Red Dollars are converted into Blue Dollars.

EXCHANGE RATE SURVEY

After you have received your dividends at the end of each period you will be asked to respond to the following question; How likely do you think it is that the exchange rate will change in the next period? Circle the number from 1 to 7 that you best represents your opinion. Circling 1 means that you think it is almost impossible that the exchange rate will change in the next period. Circling 7 means that you think it is almost certain that the exchange rate will change in the next period. Your responses will be collected before the next period starts. You will also have a record sheet on which to write down your predictions. Please be as honest and accurate as you can.

RESTRICTIONS ON HOLDING DOLLARS

There is one more important thing to remember. You must always hold at least B$200. Holding less than B$200 will cost you 1 cent Canadian for every B$100 you are below B$200 each second your Blue Dollar holdings are below B$200. For example if you hold only B$150 this will cost you 0.5 cents Canadian per second. If you to hold B$0 it would cost you 2 cent Canadian per second.

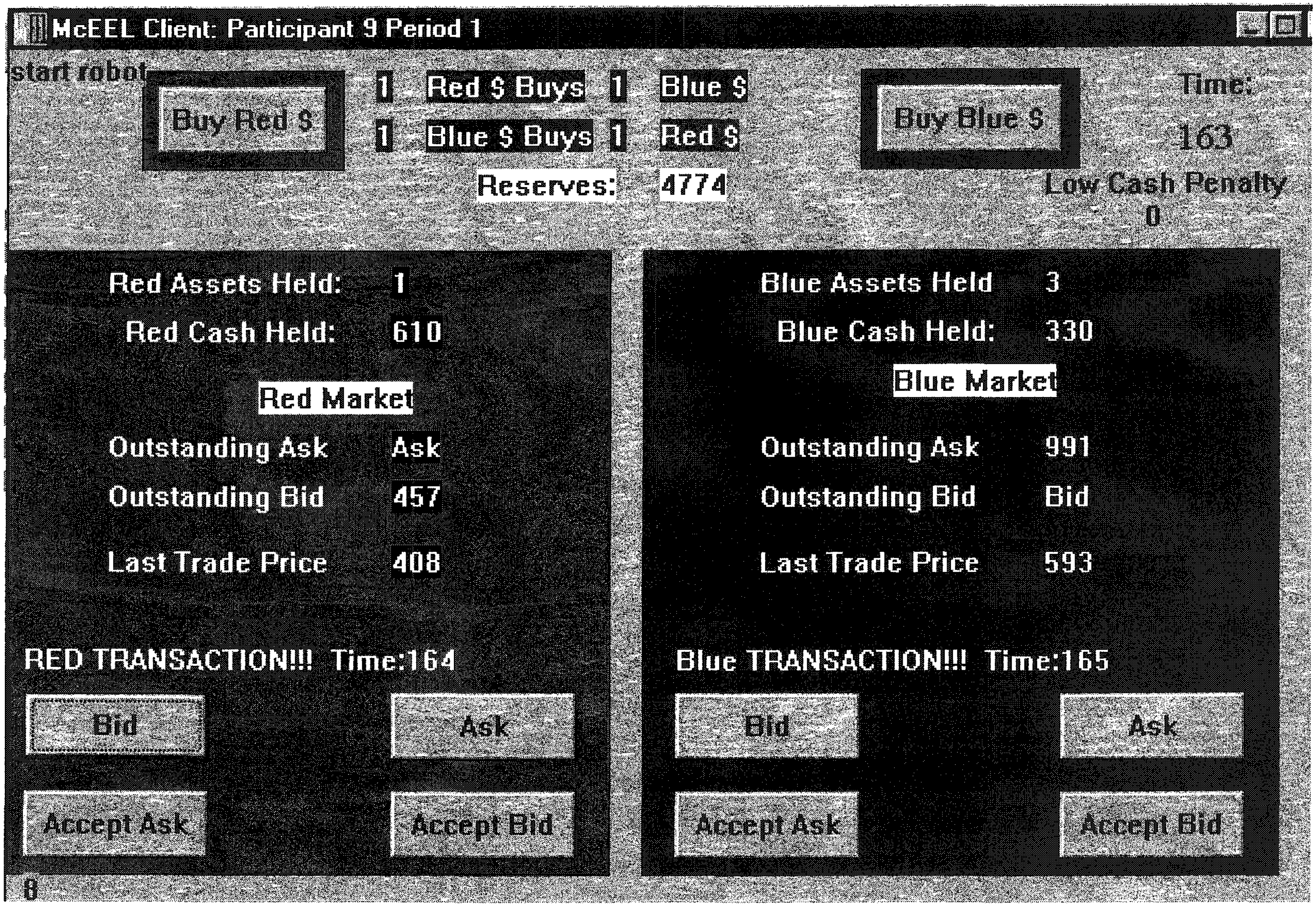
Please fill in the following table. Someone will check your work.

Blue Dollar Holdings	Cost per second
B$ 100	
B$ 300	
B$ 0	

If your holdings of Blue Dollars fall below B$200 a label will appear above the Blue Market section of your screen informing you that your holdings of Blue Dollars is low. Your total cost of holding less than B$200 is displayed on the right hand side of your screen above the Blue Market section.

Are there any questions?

Appendix 4.1
Subject's Screen



Appendix 4.2
Time Path of Subjects' Holdings of Blue Dollars

All of the figure display subjects' holdings of Blue Dollars (on the vertical axes) in real time (on the horizontal axes) for each of four sessions in the high reserve and low reserve treatment. The high reserve treatment is Treatment 1 and the low reserve treatment is Treatment 2.

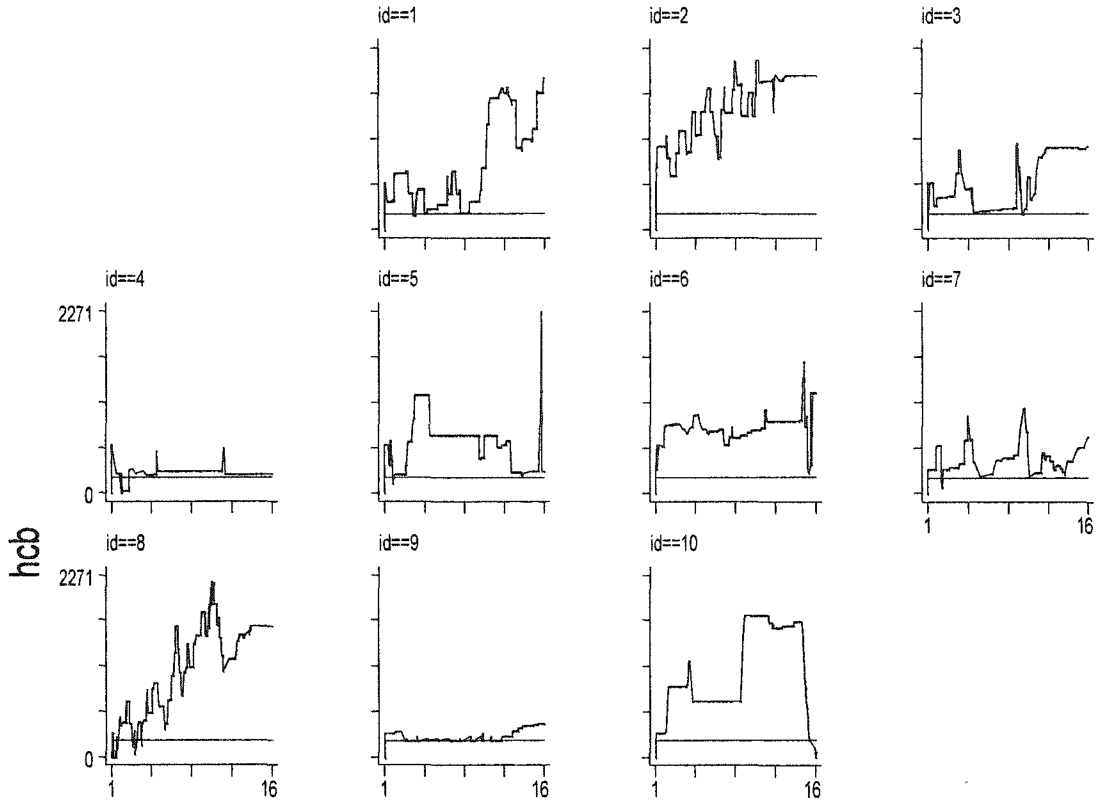


Figure A4.2.1 Treatment 1 Session 1

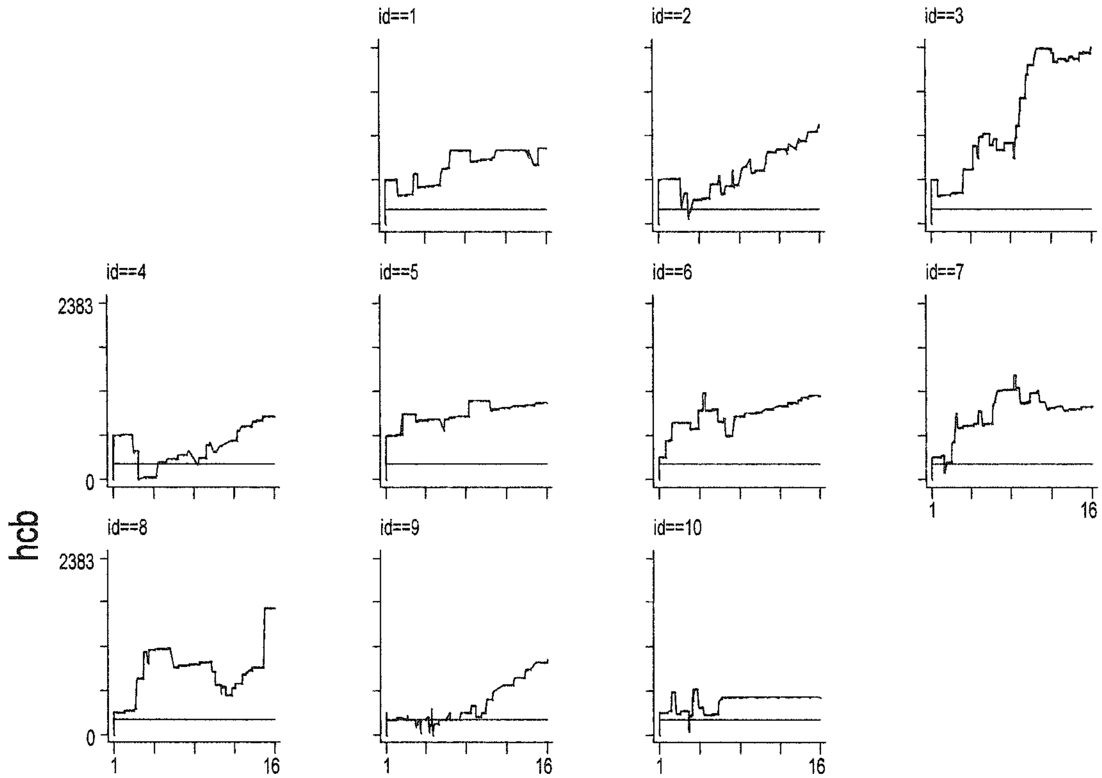


Figure A4.2.2 Treatment 1 Session 2

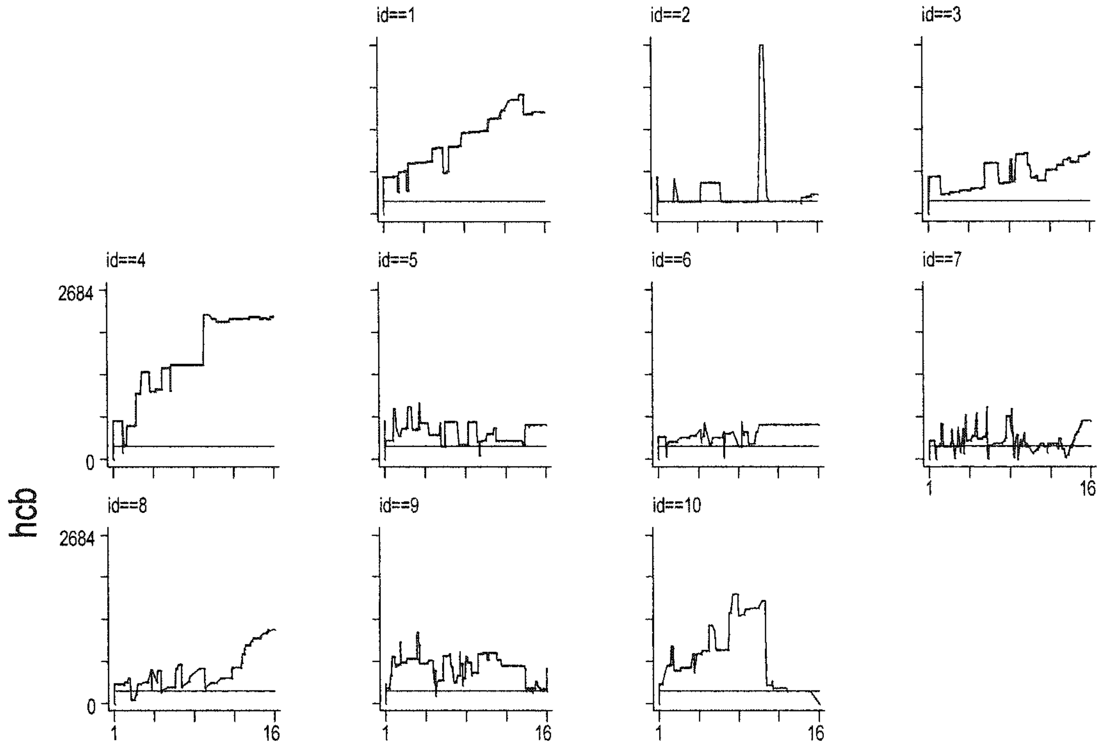


Figure A4.2.3 Treatment 1 Session 3

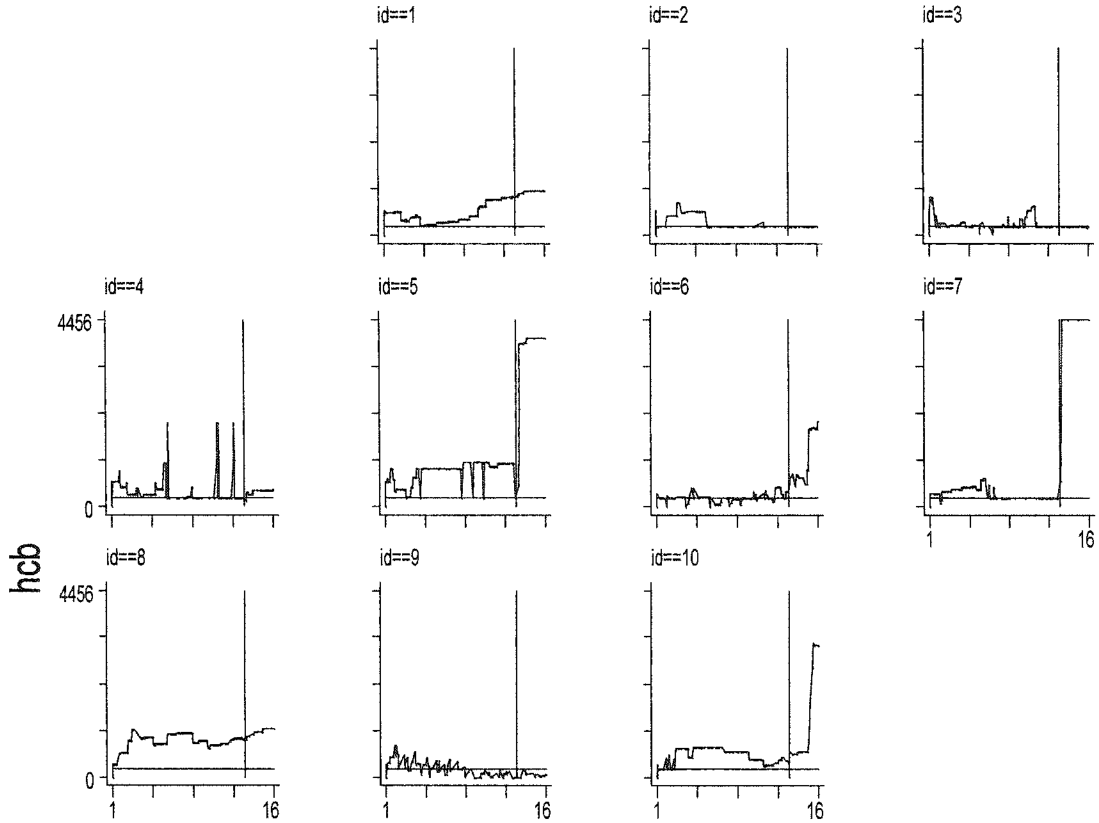


Figure A4.2.4 Treatment 1 Session 4

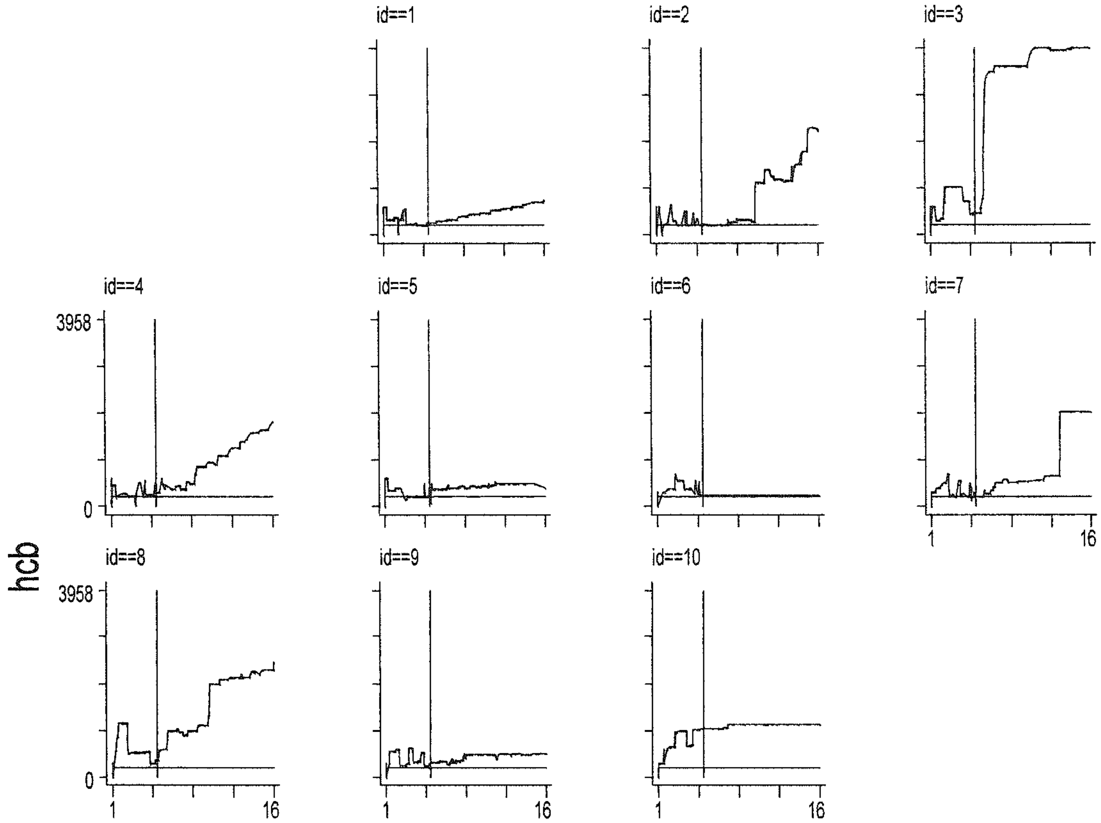


Figure A4.2.5 Treatment 2 Session 1

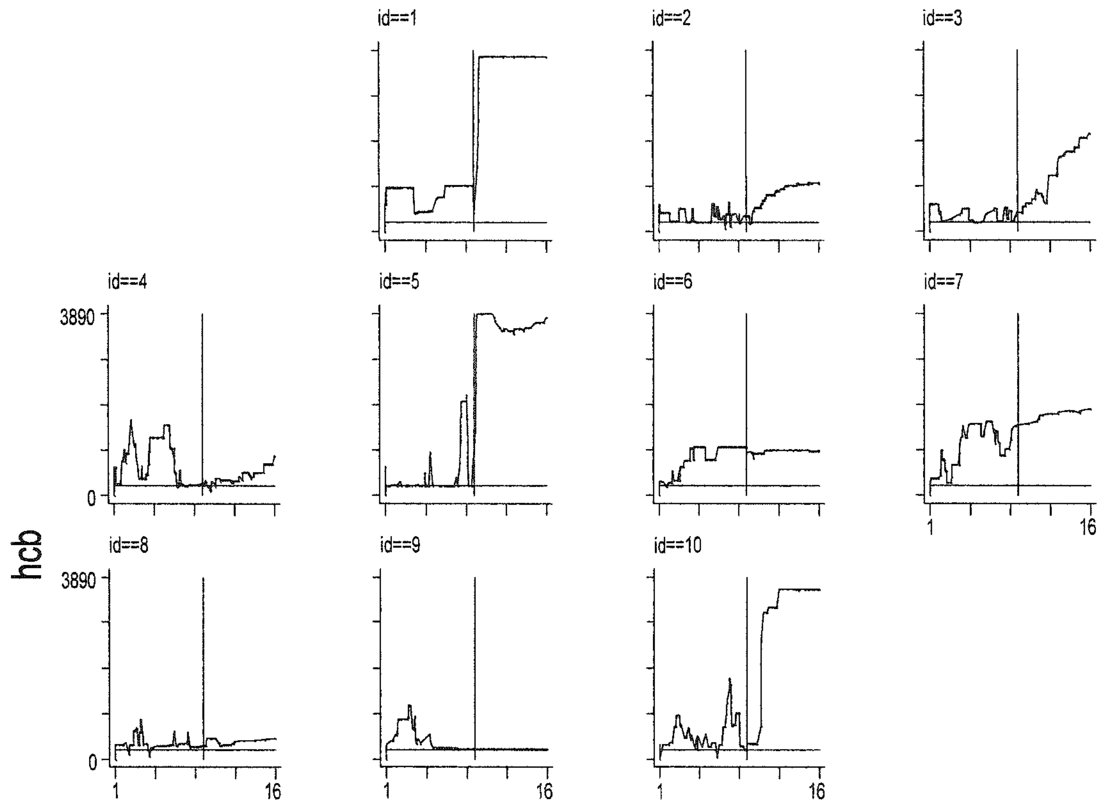


Figure A4.2.6 Treatment 2 Session 2

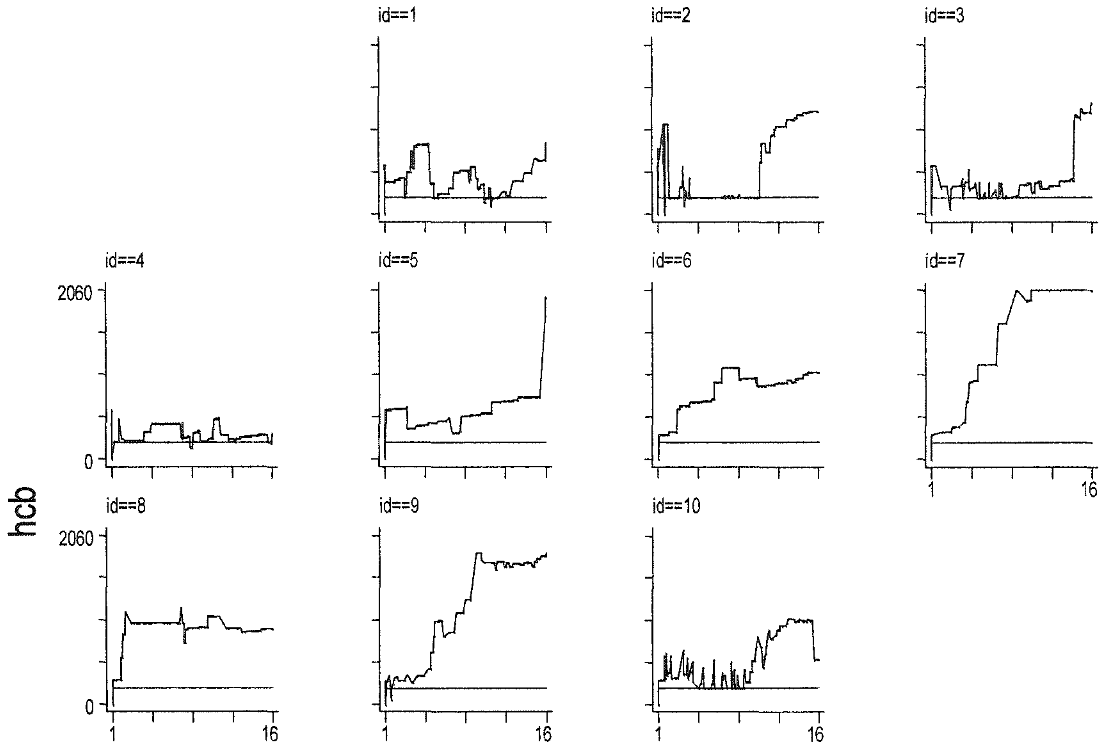
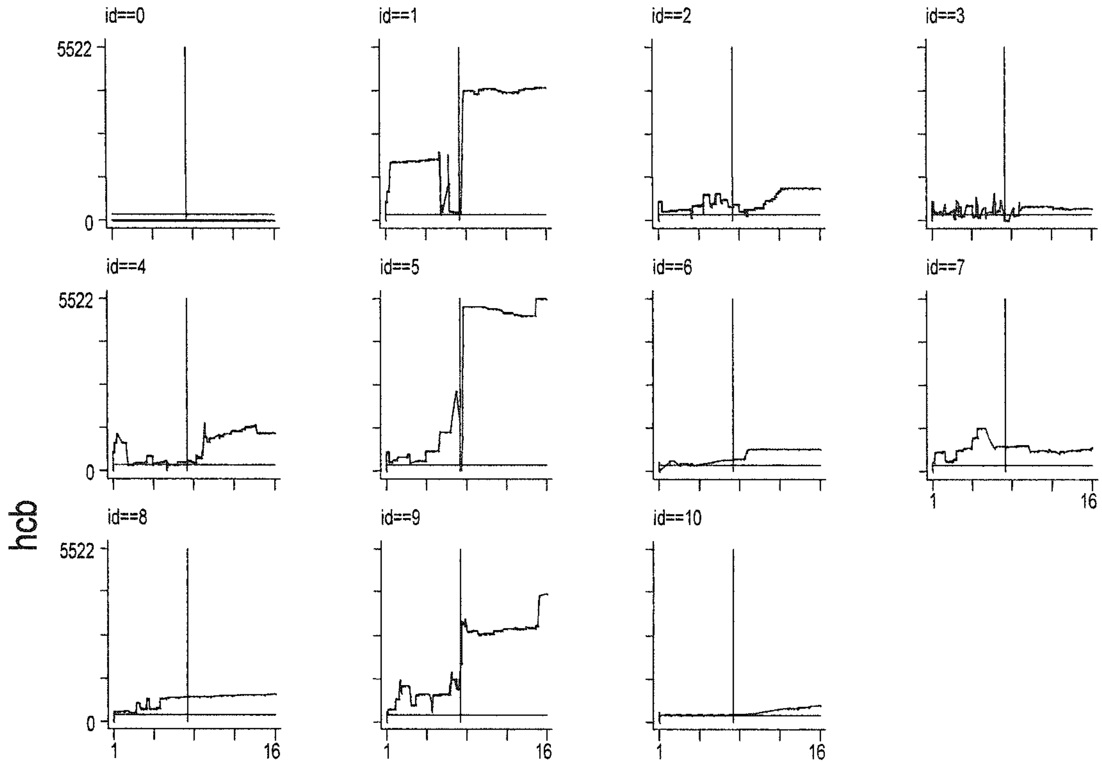
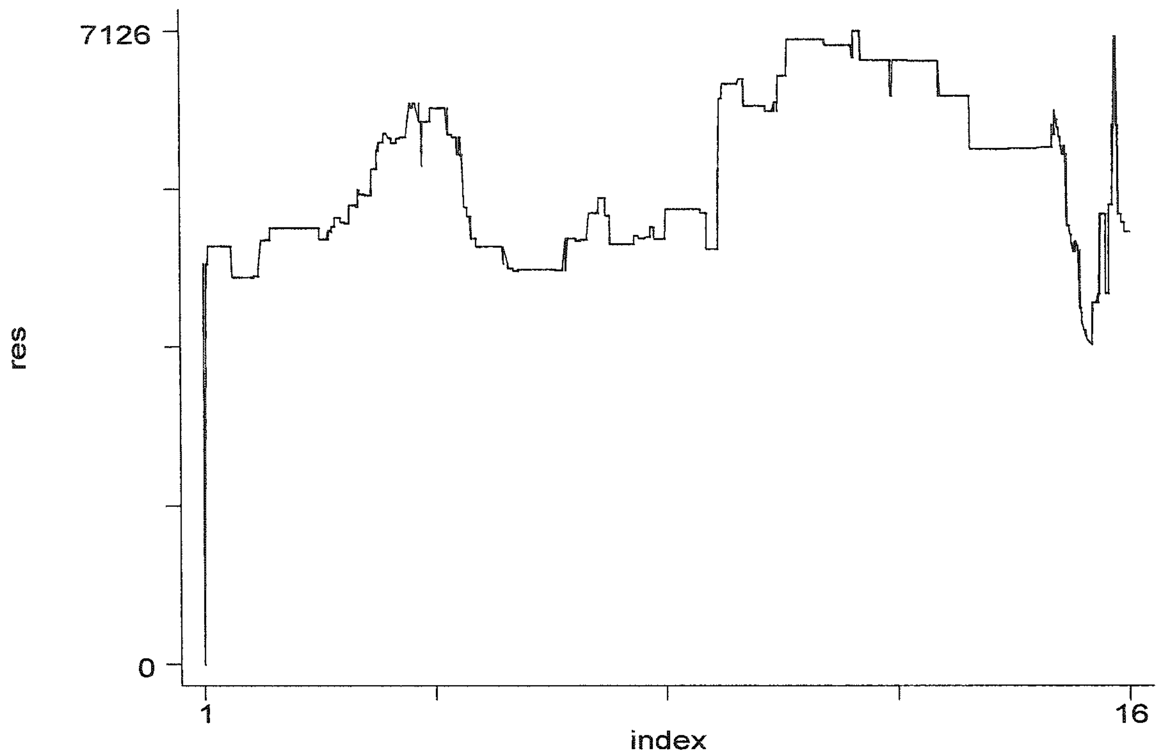


Figure A4.2.7 Treatment 2 Session 3

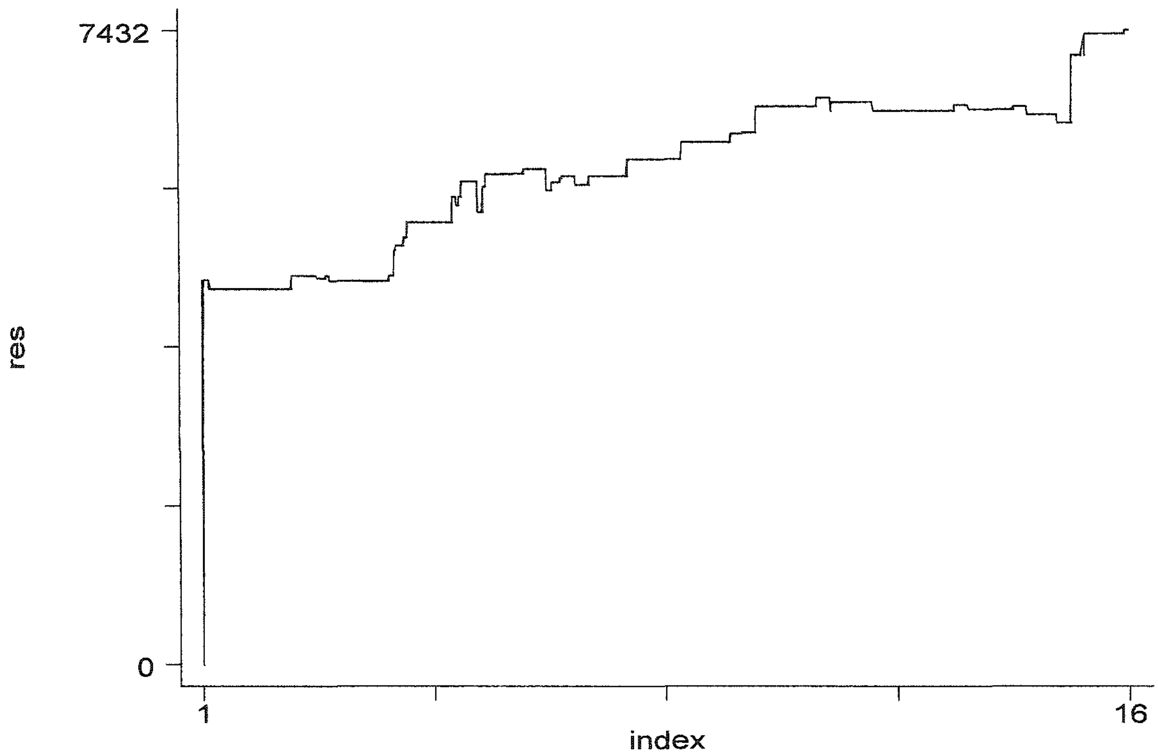


Session A4.2.8 Treatment 2 Session 4

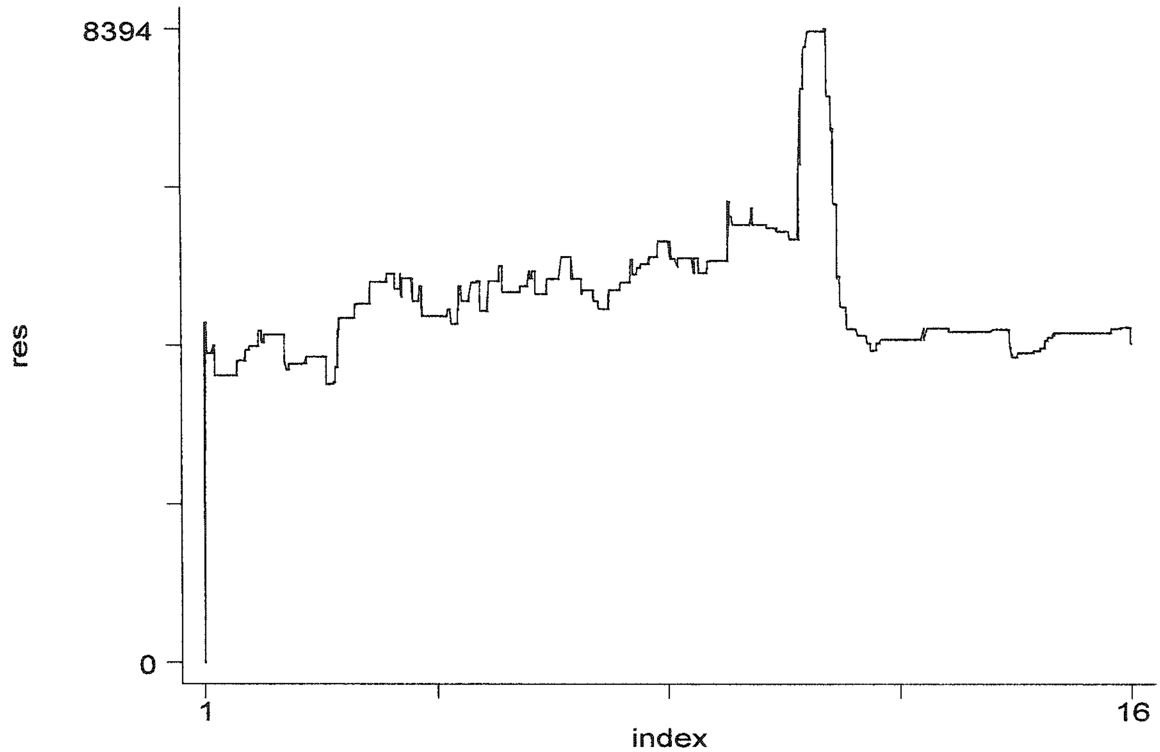
Appendix 4.3
Time Path of Reserves



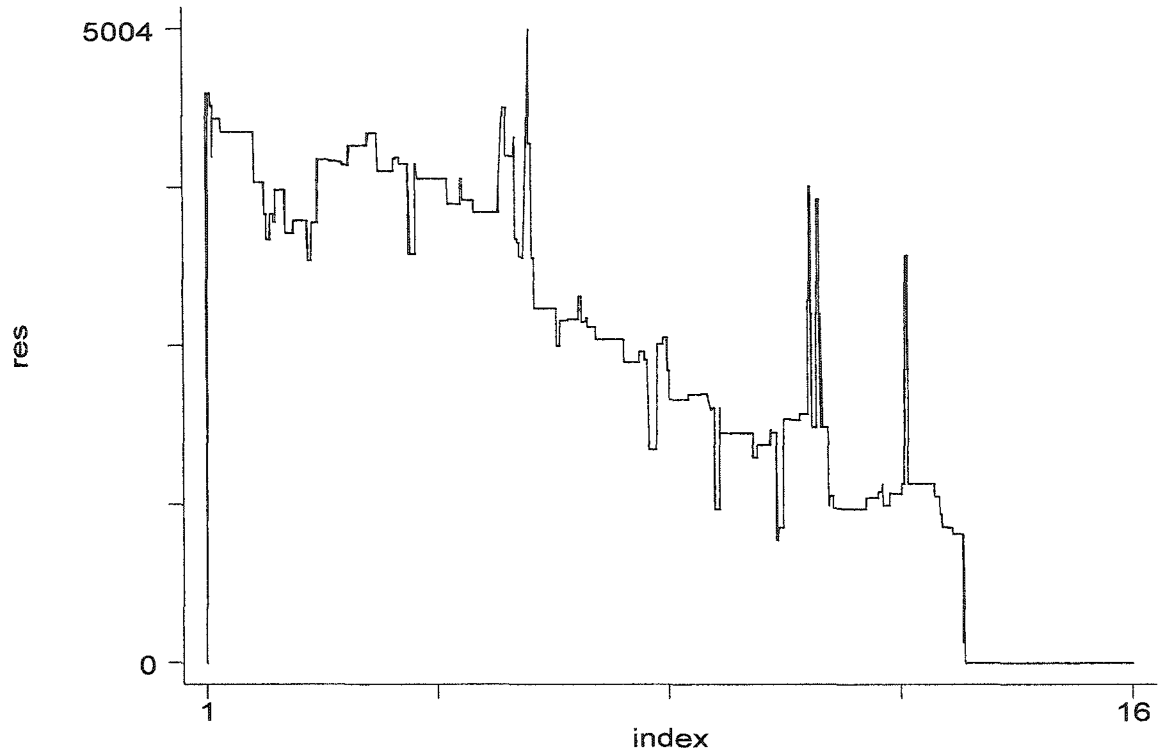
Session 1.1



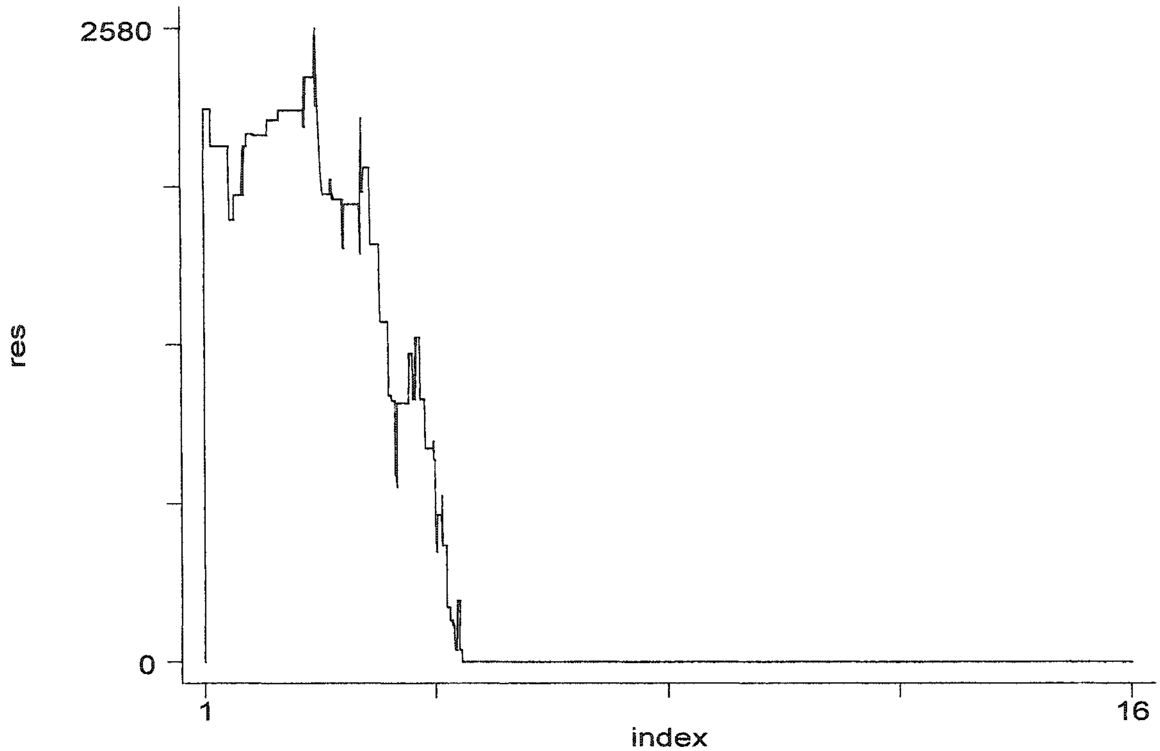
Session 1.2



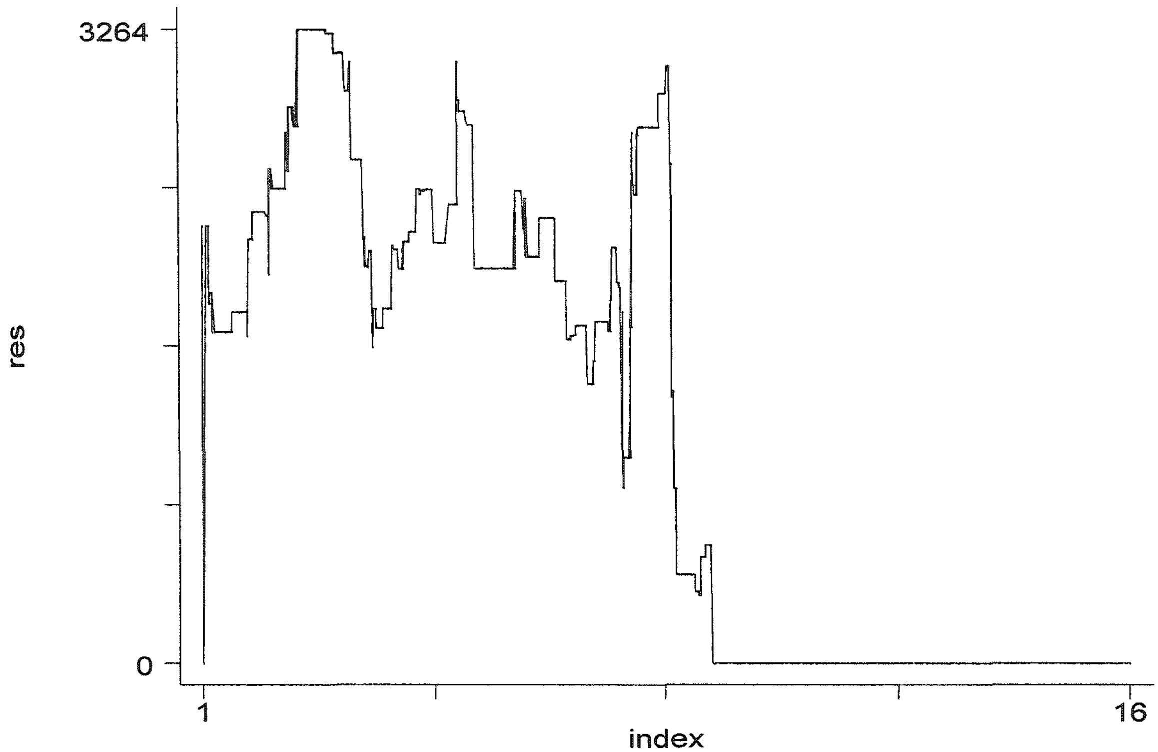
Session 1.3



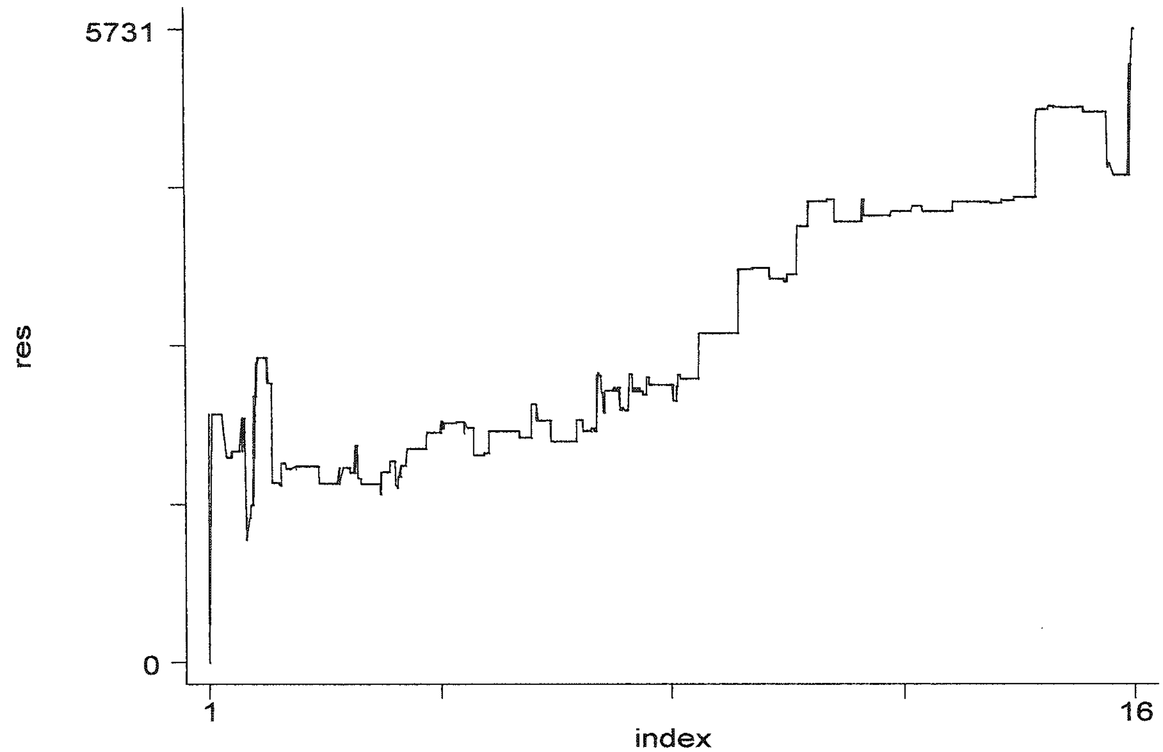
Session 1.4



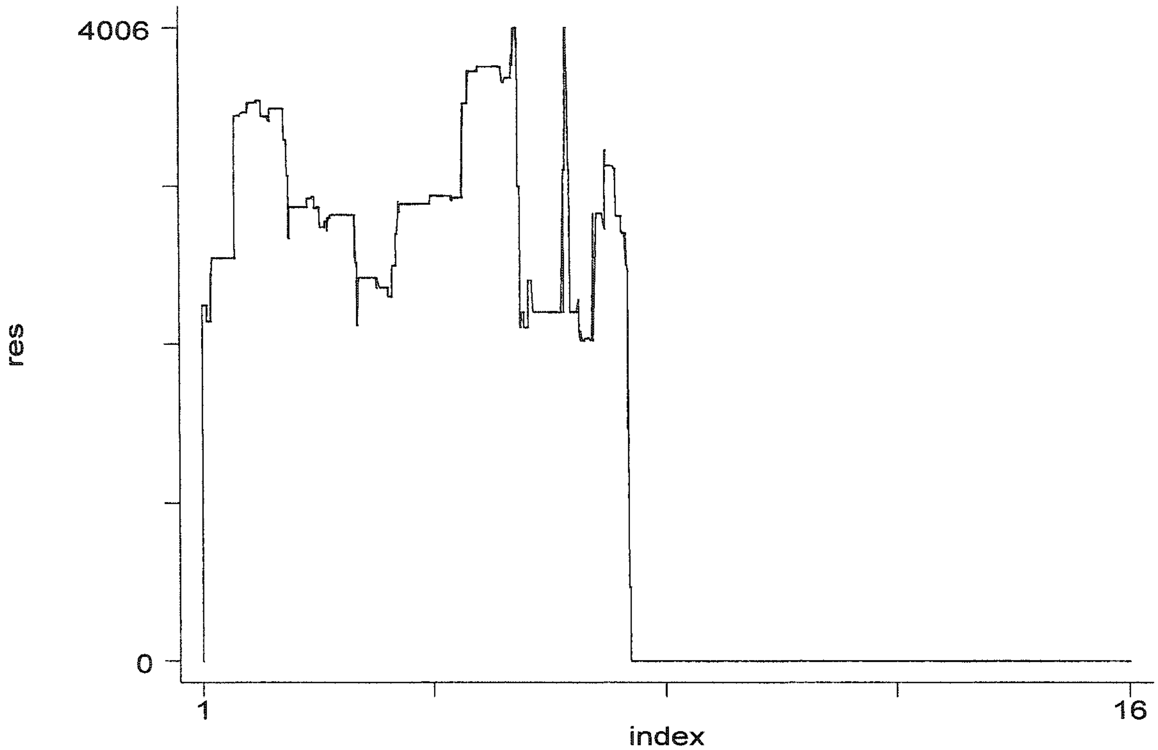
Session 2.1



Session 2.2



Session 2.3



Session 2.4

Chapter Five

Conclusions

Chapter Five
Conclusions

The work presented in the preceding chapters represents one of the first organized investigations of international finance using experimental methods. Obstfeld and Rogoff [2000] identify several of the major questions of international finance that previous research methods have yet to resolve. Two of these issues are interest rate parity and currency crises.

The idea behind interest rate parity is that once expected changes in the exchange rate between two currencies are taken into consideration the interest rates in those two countries will be the same. Interest rate parity relies on the exhaustion of all opportunities for arbitrage. Interest rate parity focuses mainly on comparing the rate of return on financial certificates, rather than financial assets in general. Thus interest rate parity is a special case of rate of return parity. The experimental environments of the preceding essays focussed on rate of return parity rather than on the special case of interest rate parity.

A special case of interest rate parity is uncovered interest rate parity. Uncovered interest rate parity has been the focus of much research in economics without many conclusive results. Some researchers have found support for uncovered interest rate parity, while others have found none. There has been no shortage of empirical methodologies applied to the problem. The techniques range from simple histograms to tests of stationarity using vector auto-regressions. With no general consensus on the applicability of uncovered interest rate parity using field data other techniques must be considered. In considering rate of return parity the issue is not interest on secure assets but the return on invested capital. Feldstein and Horika [1980] investigate the issue of capital mobility, which has dramatic implications for rate of return parity through the possible exploitation of arbitrage opportunities, by examining the correlation between internal investment rates and saving rates. The high degree of correlation between the investment rates and saving rates indicates that capital does not flow freely between countries. Thus, rate of return parity cannot be expected to hold.

One of the avenues of inquiry that has thus far not been generally applied to international finance is laboratory experimentation. Many of the difficulties encountered when using field data to address uncovered interest rate parity and other forms of rate of return parity may arise from the number of unmeasured and unmeasurable variables. A possible solution to this problem is to apply various econometric techniques. Another possible solution is to create a situation in which those factors will have a limited impact. This is the role of laboratory experimentation, the approach taken in the essays above.

The investigation of rate of return parity is divided between Chapters Two, Three, and Four. Chapter Two uses a traditional experimental approach to consider the issue. Simultaneous asset markets joined by an exchange rate with known characteristics were created. Inexperienced, non-expert subjects then participated in these markets. The data that resulted from these experiments showed a surprising degree of support for rate of return parity, particularly when the two types of assets were very similar and the exchange rate between the two currencies was perfectly fixed. As the assets become more differentiated, the support for rate of return parity declined. These results seem to indicate that the observed failure of rate of return parity in field data may be caused by a lack of comparability between assets rather than barriers to capital mobility or even exchange rate risk. Though the addition of exchange rate risk to the environment further weakens the predictive power of rate of return parity.

Chapter Three presents yet another alternative approach to investigating rate of return parity. Based on the fundamental characteristics of average transaction price data discovered during Treatment 1 of the experiments in Chapter Two robot traders are employed in an attempt to recreate similar data from known, consistently followed behavioural rules. The two characteristics that the robot traders must recreate are price bubbles and crashes and rate of return parity. The first is achieved with robots that base the price they are willing to accept or pay on a weighted average of a price trend and the fundamental dividend value of the assets in question. The second characteristic is only achieved when one of the traders is designated as an arbitrageur. This result indicates that there must be at least one human agent acting as an arbitrageur in Treatment 1 of the experiment presented in Chapter Two.

Rate of return parity is further considered in the currency crisis environment of Chapter Four. In this experimental environment it is possible that the exchange rate will change, but it is not guaranteed to do so. This environment differs from the last treatment of Chapter Two in that the exchange rate is controlled by the subjects. The level of rate of return parity observed in this environment is significantly lower than in situation in which the exchange rate is perfectly fixed.

Examination of rate of return parity is not the main goal of Chapter Four, however. The main goal of Chapter Four is to investigate currency crises using experimental techniques. The current outstanding issue surrounding currency crises is what role, if any, self-fulfilling prophecies play in such events. Studying this issue using field data is exceptionally difficult for a number of reasons, the first of which is the inability to conduct counterfactual investigations. In field data either a currency experiences a crisis or it does not. It is almost impossible to find a situation in which two currencies differ by only one factor and one experienced a crisis and the other did not. Even if it were possible to create a situation in which two currencies differed by only one factor with the express purpose of observing which currency experienced a crisis, the cost to the societies involved would be horrendous. A second difficulty in using field data to study currency crises is the number of potentially relevant factors. Anything and everything that can influence the moods of investors and speculators should be considered on some level for a complete understanding of the dynamics of the situation. This is simply impossible. For many of the variables in question data do not exist, and when data do exist, in many cases they are suspect. Given these limitations of field data, the alternative of laboratory experiments is a natural and cost effective alternative.

The laboratory environment created in Chapter Four was very similar to that used in Chapters Two and Three. The major difference being that there was a limited reserve with which the initial exchange rate was supported, rather than the exchange rate being perfectly fixed or subject to random changes. When this reserve was exhausted through exchanges of currency, the exchange rate was devalued. In three of the four sessions with the reserves initially set at 50% of the endowment of the currency in question a crisis was observed. In only one of the four sessions when the initial reserve was set to 100% of the endowment of the currency in question was a crisis observed. These outcomes lead to two important conclusions. First that individuals are able to coordinate their actions in order to cause a currency crisis to occur. Thus self-fulfilling prophecies may have an important role to play in determining if a currency crisis will occur. The second conclusion of this research is that the level of reserves held by a central bank can and does influence the frequency of currency crises, and thus implicitly the beliefs of investors and speculators. These lessons require further investigation before they should be applied to field situations, but these early results are very telling for the direction future research should take. Understanding the formation and implications of the beliefs of investors and speculators is essential to understanding currency crises.

The applications of experimental methodology to these issues of international finance represents a definite starting point to a much improved understanding of the issues involved. The results for the investigations of rate of return parity underline the importance of asset comparability in international finance markets. The results from the experiments on currency crises indicate that the beliefs of investors and speculators are central to the resolution of these events. Armed with these findings a more fruitful avenue of investigation can be undertaken using both field data and further laboratory experiments.

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