A Dynamic General Equilibrium Approach to Asset Pricing Experiments

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Abstract

We report results from a laboratory experiment that implements an infinite horizon, consumption-based general equilibrium model of asset pricing. This work-horse model of the macrofinance literature predicts that agents buy and sell assets for the purpose of intertemporally smoothing consumption and that asset prices are determined by risk and time preferences and processes for income and dividends. The experimental findings are largely supportive of the model's theoretical predictions. Notably we observe that in the environment we study, asset price *bubbles*, defined as sustained departures of prices from those implied by fundamentals, are not generally observed. This finding is a stark departure from many recent partial equilibrium, finite-horizon asset pricing experiments that lack a consumption–smoothing objective. Indeed, we find that when subjects are induced to hold assets so as to smooth consumption, assets trade at a discount relative to their expected value and markets are thick; when the consumption-smoothing motivation to trade assets is removed in an otherwise identical economy, assets trade at a premium relative to fundamentals and market volume is reduced.

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1 Introduction

The consumption-based general equilibrium approach to asset pricing, as pioneered in the work of Stiglitz (1970), Lucas (1978) and Breeden (1979), is a workhorse model in the literature on financial asset pricing in macroeconomics, or *macrofinance*. This approach relates asset prices to individual risk and time preferences, dividends, aggregate disturbances and other fundamental determinants of an asset's value.[1] While this class of theoretical models has been extensively tested using archival field data, the evidence to date has not been too supportive of the models' predictions. For instance, estimated or calibrated versions of the standard model generally under-predict the actual premium in the return to equities relative to bonds, the so-called "equity premium puzzle" (Hansen and Singleton (1983), Mehra and Prescott (1985), Kocherlakota (1996)), and the actual volatility of asset prices is typically much greater than the model's predicted volatility based on changes in fundamentals alone – the "excess volatility puzzle" (Shiller (1981), LeRoy and Porter (1981)).[2]

A difficulty with testing this model using field data is that important parameters like individual risk and time preferences, the dividend and income processes, and other determinants of asset prices are unknown and have to be calibrated, approximated or estimated in some fashion. An additional difficulty is that the available field data, for example data on aggregate consumption, are measured with error (Wheatley (1988)) or may not approximate well the consumption of asset market participants (Mankiw and Zeldes (1991)). A typical approach is to specify some dividend process and calibrate preferences using micro-level studies that may not be directly relevant to the domain or frequency of data examined by the macrofinance researcher.

In this paper we follow a different path, by designing and analyzing data from a laboratory experiment that implements a simple version of an infinite horizon, consumption–based general equilibrium model of asset pricing. In the laboratory we can control the income and dividend processes and implement the stationary associated with an infinite horizon by inducing a constant discount factor. Further, we can precisely measure individual consumption and asset holdings, and we were able to estimate each individual's risk preferences separately from those implied by his market activity, providing us with a very clear picture of the environment in which agents are make asset pricing decisions. We can also reliably induce heterogeneity in agent types so as to create a clear motivation for subjects to engage in trade, whereas the theoretical literature frequently presumes a representative agent and derives equilibrium asset prices at which the equilibrium volume of trade is zero. The degree of control afforded by the laboratory presents an opportunity to diagnosis the causes of specific deviations from the theory which are not identifiable using field data alone.

There already exists a literature testing asset price formation in the laboratory, but the design of those experiments departs in significant ways from the consumption-based general equilibrium model found in the macrofinance literature. The early experimental literature (e.g., Forsythe, Palfrey and Plott (1982), Plott and Sunder (1982) and Friedman, Harrison and Salmon (1984)) considered markets comprised of a known, finite number of 2-3 period cycles. Each subject was assigned a type that determined his endowment of cash and assets at the beginning of a cycle as well as his deterministic (but non-constant) dividend stream. Each period began with trade in the asset among subjects and ended with the payment of type-dependent dividends for each unit of the asset held. The general finding from this literature is that market prices effectively aggregate private information about dividends and tend to converge toward rational expectations values. While such results are in line with the efficient markets view of asset pricing, the primary motivation for exchange in these experimental designs is owing to heterogenity in the value of dividends rather than

[1]See, e.g., Cochrane (2005) and Lengwiler (2004) for surveys.

[2]Nevertheless, as Cochrane (2005, p. 455) observes, while the consumption-based model "works poorly in practice...it is in some sense the only model we have. The central task of financial economics is to figure out what are the real risks that drive asset prices and expected returns. Something like the consumption-based model–investor's first-order conditions for savings and portfolio choice–has to be the starting point."

intertemporal consumption-smoothing as in the framework we study.

In later, highly influential work by Smith, Suchanek, and Williams (SSW) (1988), a simple four-state i.i.d. dividend process was made common for all subjects. A finite number of trading periods ensured that the fundamental value of the asset declined at a constant rate over time. There was no induced motive for subjects to engage in any trade at all. Nevertheless, SSW observed substantial trade in the asset, with prices typically starting out below the fundamental value, then rapidly soaring above the fundamental value for a sustained duration of time before collapsing near the end of the experiment. The "bubble-crash" pattern of the SSW design has been replicated by many authors under a variety of different treatment conditions, and has become the primary focus of the large and growing experimental literature on asset price formation (key papers include Porter and Smith (1995), Lei et al. (2001), Dufwenberg, et al. (2005), Haruvy et al. (2007) and Hussam et al. (2008); for a review of the literature, see chapters 29 and 30 in Plott and Smith (2008)). Despite many treatment variations (e.g., incorporating short sales or futures markets, computing expected values for subjects, implementing a constant dividend, inserting "insiders" with previous experience in bubbles experiments, using professional traders in place of students as subjects), the only reliable means of eliminating the bubble-crash pattern in the SSW environment has been to repeat the same market trading conditions several times with the same group of subjects.[3]

There also exists an experimental literature testing the capital-asset pricing model (CAPM), see, e.g., Bossaerts and Plott (2002), Asparouhova, Bossaerts, and Plott (2003), Bossaerts, Plott and Zame (2007). By contrast with the consumption-based approach to asset pricing, the CAPM is a *portfolio-based* approach and presumes that agents have no other source of income apart from asset income. Another important distinction is that the CAPM is not an explicitly dynamic model; laboratory investigations of the CAPM involve repetition of a static, one-period economy.[4]

Our focus on the consumption-based approach to asset pricing also establishes a bridge between the experimental literatures on asset pricing and intertemporal consumption-smoothing. Experimental investigation of intertemporal consumption smoothing (without tradeable assets) is the focus of papers by Hey and Dardanoni (1988), Noussair and Matheny (2000), Ballinger et al. (2003) and Carbone and Hey (2004). A main finding from that literature is that subjects appear to have difficulty intertemporally smoothing consumption in the manner prescribed by the solution to a dynamic optimization problem; in particular, current consumption appears to be too closely related to current income relative to the predictions of the optimal consumption function. By contrast, in our experimental design where intertemporal consumption smoothing must be implemented by buying and selling assets at market-determined prices, we find strong evidence that subjects are able to consumption-smooth in a manner that approximates the dynamic, equilibrium solution. This finding suggests that asset-price signals may provide an important coordination mechanism enabling individuals to more readily implement near-optimal consumption and savings plans.

Our aim in implementing an experimental general equilibrium asset pricing model that is closely aligned with the theory and predictions of the macrofinance literature is to begin a dialogue between macrofinance researchers and experimentalists. Our design enables us to address a number of issues related to asset pricing and intertemporal decision-making while incorporating several important insights gained from the experimental asset pricing and consumption-smoothing literatures.

One way in which we depart from the existing experimental asset pricing literature is that we induce "consumption" at the end of every period, (as *is* done in the experimental literature on consumption-smoothing). In experimental asset pricing experiments, (e.g., SSW and others), subjects are loaned a large

[3] Lugovskyy, Puzzello, and Tucker (2010) have recently implemented the SSW framework using a tatonnement institution in place of the double auction and report a significant reduction in the incidence of bubbles.

[4] Cochrane (2005) points out that intertemporal versions of the CAPM can be viewed as a special case of the consumption-based approach to asset pricing where the production technology is linear and there is no labor/endowment income.

quantity of experimental currency units ("francs") at the beginning of a session. This loan must be repaid at the end of a session (involving many trading periods); subjects' remaining franc balance (after repayment of the loan) are converted into dollars at a linear exchange rate. This feature differs from the sequence–of–budget constraints faced by agents in standard intertemporal asset pricing models, and may promote high asset prices. In our design, subjects receive an exogenous franc income at the beginning of each new period, as in a pure exchange economy. Dividends are paid on assets held and then the market is opened for trade in the asset. End-of-period franc balances are converted into dollars and stored in the subjects' payment accounts, so that at the end of each period all francs disappear entirely from the system. Thus in our framework, assets are durable "trees" and francs were perishable "fruit" in the language of Lucas (1978).

A second way in which we depart from the existing experimental literature is that we induce heterogenity in agent endowments which, together with a concave utility function objective, provides a motivation for trade in the asset. Specifically, in one of our treatments the franc-to-dollar exchange rate is concave, so that long-lived assets became a vehicle for intertemporally smoothing consumption. This feature is a critical component of most macrofinance models which are built around the permanent income model of consumption (and, indeed, this feature is also present in experimental studies of intertemporal consumption/savings decisions) but it is absent from the experimental asset pricing literature. In a second treatment, the franc-to-dollar exchange rate is made linear, as in the experimental asset pricing literature. Since the dividend process is common to all subjects, in the latter, "linear" exchange rate treatment there is no induced reason for subjects to trade in the asset, thus connecting a macrofinance economy with the laboratory asset bubble design of SSW.

Most consumption-based asset pricing models posit infinite planning horizons. A third distinguishing feature of our design is that we induce the stationary of an infinite horizon by implementing discounting of future payoffs. By contrast, in the SSW experimental asset pricing design (as well as others found in the literature) a finite horizon is implemented with no discounting leading to a steadily declining fundamental value for the asset. We induce discounting by introducing a constant probability that assets would become worthless at the end of each period.[5] Thus from the decision-maker's perspective, francs today are worth more than identical francs tomorrow, not because the subject is impatient but because future earnings are less likely to be realized. One minus this continuation probability has a natural interpretation as firm *bankruptcy risk* (i.e., the firm issuing the asset goes bankrupt and the asset becomes worthless). If subjects are risk neutral, expected utility maximizers, our indefinite horizon economies feature the same steady state equilibrium price and shareholdings as their infinite horizon analogues.

A fourth feature of our design is that we consider the consequences of departures from risk neutral behavior. Our analysis of this issue is both theoretical and empirical. Specifically, we elicit a measure of risk tolerance from subjects in most of our experimental sessions using the Holt-Laury (2002) paired lottery choice instrument. To our knowledge no prior study has seriously investigated risk preferences in combination with a multi-period asset pricing experiment. Our evidence on risk preferences, elicited from participants who have also determined asset prices in a dynamic general equilibrium setting, should be of interest to macrofinance researchers investigating the "puzzles" in the asset pricing literature; for example, the equity premium puzzle and the related risk-free rate puzzle depend on assumptions made about risk attitudes, which, to date has been derived from survey and experimental studies that do not involve asset pricing (see, e.g., the discussion in Lengwiler (2004).

Our experiment has yielded a number of interesting findings. First, the presence of "bankruptcy risk" in the linear exchange rate environment (where, as in SSW, there is no motivation for asset trade) does

[5] Camerer and Weigelt (1993) used such a device to study asset price formation within the heterogeneous dividends framework referenced earlier. Their main finding is that asset prices converge slowly and unreliably to predicted levels from below.

not suffice to eliminate asset price "bubbles." Indeed, we often observe sustained deviations of prices above fundamentals in this environment. However, the frequency, magnitude, and duration of asset price bubbles are substantially mitigated when we induce a concave exchange rate (utility function); in the "concave" treatment, assets tend to trade at a discount relative to their expected value. The higher prices in the linear utility economies are driven by a concentration of shares among the most risk-tolerant subjects in the market as revealed by separately elicited measure of risk attitudes. By contrast, in the concave exchange rate treatment, most subjects actively trade shares in each period to smooth their consumption in the manner predicted by theory, so that shareholdings are much less concentrated relative to the linear treatment. Thus market thin-ness and high prices appear to be endogenous features of speculative markets in our design. We conclude that the frequency, magnitude, and duration of asset price bubbles can be greatly reduced by the presence of an incentive to intertemporally smooth consumption in an otherwise identical economy.

2 A simple asset pricing framework

In this section we describe the consumption-based asset pricing framework that we implemented in the laboratory. In particular, we consider a heterogeneous agent version of Lucas's (1978) one-tree model. In line with the theory, we assume subjects in the experiment are risk-neutral expected utility maximizers so that the infinite horizon model we present here shares a (unique) steady-state equilibrium with the stochastic horizon economy we actually implement in the laboratory. In Section 5 we relax this assumption and consider how the model is impacted by departures from risk neutrality.

We consider an economy where time, t, is discrete and there are two agent types, $i = 1, 2$, who participate in an infinite sequence of markets. There is a fixed supply of the infinitely durable asset (trees), each unit of which yields some stochastic dividend (fruit) in amount d_t per period. Dividends are paid in units of the single non-storable consumption good at the beginning of each period. Let s_t^i denote the number of asset shares agent i owns at the beginning of period t, and let p_t be the price of the asset in period t. In addition to dividend payments, agent i receives an exogenous endowment of the consumption good y_t^i at the beginning of every period; his initial endowment of shares is denoted s_1^i.

Agent i seeks to maximize:

$$\max_{\{c_t^i\}_{t=1}^{\infty}} E_1 \sum_{t=1}^{\infty} \beta^{t-1} u^i(c_t^i),$$

subject to

$$c_t^i \leq y_t^i + d_t s_t^i - p_t \left(s_{t+1}^i - s_t^i\right)$$

and a transversality condition. Here, c_t^i denotes consumption of the single perishable good by agent i in period t, $u^i(\cdot)$ is a strictly monotonic, strictly concave, twice differentiable utility function, and $\beta \in (0, 1)$ is the (common) discount factor. The budget constraint is satisfied with equality by monotonicity. We will impose no borrowing and no short sale constraints on subjects in the experiment, but the economy will be parameterized in such a way that these restrictions only bind out-of-equilibrium. Substituting the budget constraint for consumption in the objective function, and using asset shares as the control, we can restate the problem as:

$$\max_{\{s_{t+1}^i\}_{t=1}^{\infty}} E_1 \sum_{t=1}^{\infty} \beta^{t-1} u^i(y_t^i + d_t s_t^i - p_t(s_{t+1}^i - s_t^i)).$$

The first order condition for each time $t \geq 1$, suppressing agent superscripts for notational convenience, is:

$$u'(c_t)p_t = E_t \beta u'(c_{t+1})(p_{t+1} + d_{t+1}).$$

Rearranging we have the asset pricing equation:

$$p_t = E_t \mu_{t+1}(p_{t+1} + d_{t+1}) \tag{1}$$

where $\mu_{t+1} = \beta \frac{u'(c_{t+1})}{u'(c_t)}$, a term that is referred to variously as the stochastic discount factor, the pricing kernel, or the intertemporal marginal rate of substitution. If we assume, for example, that $u(c) = \frac{c^\gamma}{1-\gamma}$ (the commonly studied CRRA utility), we have $\mu_{t+1} = \beta \left(\frac{c_t}{c_{t+1}}\right)^\gamma$. Notice from equation (1) that the price of the asset depends on 1) individual risk parameters such as γ; 2) the rate of time preference r, which is implied by the discount factor $\beta = 1/(1+r)$; 3) the income process; and 4) the dividend process, which is assumed to be known and common to both agents.

In our experiment units of the consumption good are referred to as "francs," which also serve as the numeraire for endowment income, asset prices and dividends. Shares of the asset are simply referred to as "assets". The utility function $u^i(c^i)$ serves as a map from subject i's end-of-period franc balance (consumption) to U.S. dollars. Dollars accumulate across periods and are paid in cash at the end of the experiment. After the francs for a given period are converted into dollars they *disappear from the system*, as the consumption good is not storable. In all sessions of the experiment we restrict the aggregate endowment of francs and assets to be constant across periods and this fact was public knowledge.[6] We also set the dividend equal to a constant value, that is, $d_t = \bar{d}$ for all t, and made this fact public knowledge so that a constant steady state equilibrium price exists.[7] Under the constant dividend assumption, applying some algebra to equation (1) yields:

$$p^* = \frac{\bar{d}}{E_t \frac{u'(c_t)}{\beta u'(c_{t+1})} - 1}. \tag{2}$$

This equation applies to each agent, so if one agent expects consumption growth or decay they all must do so in equilibrium. Since the aggregate endowment is constant, strict monotonicity of preferences implies that there can be no growth or decay in consumption for all individuals in equilibrium. Thus it must be the case that in a steady state competitive equilibrium each agent perfectly smoothes his consumption, that is, $c_t^i = c_{t+1}^i$, so equation (2) simplifies to the standard *fundamental price* equation:

$$p^* = \frac{\beta}{1-\beta}\bar{d}. \tag{3}$$

3 Experimental design

We conducted sixteen laboratory sessions of a 6-fold replica of the economy introduced above. Thus in each session there were twelve subjects, six of each induced type, for a total of 192 subjects. The endowments of the two subject types and their utility functions are given in the table below.

Type	No. Subjects	s_1^i	$\{y_t^i\} =$	$u^i(c) =$
1	6	1	110 if t is odd, 44 if t is even	$\delta^1 + \alpha^1 c^{\phi^1}$
2	6	4	24 if t is odd, 90 if t is even	$\delta^2 + \alpha^2 c^{\phi^2}$

[6] The absence of income growth rules out the possibility of "rational bubbles".

[7] If the dividend is stochastic, it is straightforward to show that a steady state equilibrium price does not exist. Instead, the price will depend (at a minimum) upon the current realization of the dividend. See Mehra and Prescott (1985) for a derivation of equilibrium pricing in the representative agent version of this model with a finite-state Markovian dividend process. We adopt the simpler, constant dividend framework since our primary motivation was to induce an economic incentive for exchange in a standard macrofinance setting. We note that Porter and Smith (1995) show that implementing constant dividends in the SSW design does not substantially reduce the incidence or magnitude of price bubbles.

In every session the franc endowment y_t^i for each type $i = 1, 2$ followed a known deterministic two-cycle. Subjects were informed that the aggregate endowment of income and shares shares would remain constant throughout the session, but otherwise were only privy to information regarding their own income process, shareholdings, and induced utility functions. Utility parameters in all treatments were chosen so that, in equilibrium, each subject would earn \$1 per period. The utility function was presented to each subject as a table converting his end–of–period franc balance into dollars (this schedule was also represented and shown to subjects graphically). By inducing agents to hold certain utility functions, we were able to exert some degree of control over individual preferences and provide a rationale for trade in the asset.

We used a 2×2 experimental design where the treatment variables are the induced utility functions (concave or linear) and the asset dividend ($\bar{d} = 2$ or $\bar{d} = 3$).[8] In our baseline, concave treatments we set $\phi^i < 1$ and $\alpha^i \phi^i > 0$.[9] Given our two-cycle income process, it is straightforward to show that steady state shareholdings must also follow a two-cycle between the initial share endowment, $s_{odd}^i = s_1^i$, and

$$s_{even}^i = s_{odd}^i + \frac{y_{odd}^i - y_{even}^i}{\bar{d} + 2p*}. \tag{4}$$

Notice that in equilibrium subjects smooth consumption by buying asset shares during high income periods and selling asset shares during low income periods. In the treatment where $\bar{d} = 2$, the equilibrium price is $p^* = 10$. Thus in equilibrium, a type 1 subject holds 1 share in odd periods and 4 shares in even periods, and a type 2 subject holds 4 shares in odd periods and 1 share in even periods. In the treatment where $\bar{d} = 3$, the equilibrium price is $p^* = 15$. In equilibrium, type 1 subjects cycle between 1 and 3 shares, while type 2 subjects cycle between 4 and 2 shares. In autarky (no asset trade), each subject earns \$1 every two periods which is only one-half of equilibrium earnings, so the incentive to smooth consumption was reasonably strong.

Our primary variation on the baseline concave treatments was to set $\phi^i = 1$ for both agent types so that there was no longer an incentive to smooth consumption.[10] Our aim in these linear treatments was to examine an environment that was closer to the SSW framework. In SSW's design, dividends were common to all subjects and dollar payoffs were linear in francs, so risk-neutral subjects had no induced motivation to engage in any asset trade. We hypothesized that in our linear utility treatment we might observe asset trade at prices greater than the fundamental price, in line with SSW's bubble findings.

To derive the equilibrium price in the linear utility treatment (since the first-order conditions no longer apply), suppose there exists a steady state equilibrium price $\hat{p}$. Substituting in each period's budget constraint we can re-write $U = \sum_{t=1}^{\infty} \beta^{t-1} u(c_t)$ as

$$U = \sum_{t=1}^{\infty} \beta^{t-1} y_t + (d + \hat{p}) s_1 + \sum_{t=2}^{\infty} \beta^{t-2} \left[\beta d - (1 - \beta)\hat{p}\right] s_t. \tag{5}$$

Notice that the first two right-hand side terms in (5) are constant, because they consist entirely of exogenous, deterministic variables. If $\hat{p} = p^*$, the third right-hand term in (5) is equal to zero regardless of future shareholdings, $\{s_t\}_{t=2}^{\infty}$, so clearly this is an equilibrium price where the corresponding individual equilibrium shareholdings are restricted to sum to the aggregate endowment of shares in each period. If $\hat{p} > p^*$, the third right-hand term is negative, so each agent would like to hold zero shares, but this cannot be an equilibrium since excess demand would be negative. If $\hat{p} < p^*$, this same term is positive, so each agent would like to buy

[8] While the difference in the dividend values is small, the difference in the implied equilibrium prices and shares traded is much larger larger, as shown below. We did not want the differences in equilibrium prices and quantities to be too large as we chose to keep the number of assets and the two-cycle endowment of francs constant across all treatments.

[9] Specifically, $\phi^1 = -1.195$, $\alpha^1 = -311.34$, $\delta^1 = 2.6074$, $\phi^2 = -1.3888$, $\alpha^2 = -327.81$, and $\delta^2 = 2.0627$.

[10] In these linear treatments, $\alpha^1 = 0.0122, \alpha^2 = 0.0161$, and $\delta 1 = \delta^2 = 0$.

as many shares as his no borrowing constraint would allow in each period, thus resulting in positive excess demand. Thus p^* is the unique steady state equilibrium price in the case of linear utility.

In all sessions of our experiment we imposed the following trading constraints on subjects:

$$y_t^i + d_t s_t^i - p_t(s_{t+1}^i - s_t^i) \geq 0,$$

$$s_t^i \geq 0,$$

where the first constraint is a no borrowing constraint and the second is a no short sales constraint. These constraints do not impact the fundamental price in either treatment nor on steady-state equilibrium shareholdings in the concave treatment. They do restrict the set of equilibrium shareholdings in the linear treatment, which without these constraints must merely sum to the aggregate share endowment. No borrowing or short sales are standard restrictions on out-of-equilibrium exchange in market experiments.

3.1 Inducing time discounting (or bankruptcy risk)

An important methodological issue is how to induce time discounting and the stationarity associated with an infinite horizon. We follow Camerer and Weigelt (1993) and address this issue by converting the infinite horizon economy to one with a stochastic number of trading periods. Subjects participate in a number of "sequences," with each sequence consisting of a number of trading periods. Each trading period lasts for three minutes during which time units of the asset can be bought and sold by all subjects in a centralized marketplace (more on this below). At the end of each three minute trading period subjects take turns rolling a six-sided die in public view of all other participants. If the die roll results in a number between 1 and 5 inclusive, the current sequence continues with another three minute trading period. Each individual's asset position at the end of period t is carried over to the start of period $t+1$, and the common, fixed dividend amount $\overline{d}$ is paid on each unit carried over. If the die roll comes up 6, the sequence of trading periods is declared over and all subjects' assets are declared worthless. Thus, the probability that assets continue to have value in future trading periods is 5/6 (.833), which is our means of implementing time discounting, i.e. a discount factor $\beta = 5/6$. We demonstrate in section 5 that this indefinite horizon economy has the same steady state price and equilibrium shareholdings as the infinite horizon economy, provided that subjects are risk neutral. We also consider the consequences for prices and allocations when subjects deviate from the assumption of risk neutrality.

The fact that the asset may become worthless at the conclusion of any period has a natural interpretation as *bankruptcy risk*, where the (exogenous) dividend-issuing firm becomes completely worthless with constant probability. This type of risk is *not* present in any existing experimental asset pricing models aside from Camerer and Weigelt's (1993) study. For instance, in SSW the main risk that agents face is *price risk* – uncertainty about the future price of assets – as it is known that assets are perfectly durable and will continue to pay a stochastic dividend (with known support) for T periods, after which time all assets will cease to have value.[11] However, participants in naturally occurring financial markets face both price risk *and* bankruptcy risk, (as the recent financial crisis has made rather clear). It is therefore of interest to examine asset pricing in environments where both types of risk are present; for instance, it is possible that bankruptcy risk might interact with indigenous subject risk aversion to inhibit the formation of asset price bubbles.

To give subjects experience with the possibility that their assets might become worthless, our experimental sessions were set up so that there would likely be several sequences of trading periods. We recruited subjects for a three hour block of time. We informed them they would participate in one or more "sequences," each consisting of an indefinite number of "trading periods" for at least one hour after the instructions had been

[11] There is also some dividend risk but it is relatively small given the number of draws relative to states.

read and all questions answered. Following one hour of play (during which time one or more sequences were typically completed), subjects were instructed that the sequence they were currently playing would be the last one played, i.e., the next time a 6 was rolled the session would come to a close. This design ensured that we would get a reasonable number of trading periods, while at the same time limited the possibility that the session would not finish within the 3-hour time-frame for which subjects had been recruited. Indeed, we never failed to complete the final sequence within three hours.[12] The expected mean (median) number of trading periods per sequence in our design is 6 (4), respectively. The realized mean (median) were 5.3 (4) in our sessions. On average there were 3.3 sequences per session.

3.2 The trading mechanism

An important methodological issue is how to implement asset trading. General equilibrium models of asset pricing simply combine first-order conditions for portfolio choices with market clearing conditions to obtain equilibrium prices, but do not specify the actual mechanism by which prices are determined and assets are exchanged. Here we adopt the double auction as the market mechanism as it is well known to reliably converge to competitive equilibrium outcomes in a wide range of experimental markets. We use the double auction module found in Fischbacher's (2007) z-Tree software. Specifically, prior to the start of each three minute trading period t, each subject i was informed of his beginning of period asset position, s_t^i, and the number of francs he would have available for trade in the current period, equal to $y_t^i + s_t^i\bar{d}$. The dividend, $\bar{d}$, paid per unit of the asset held at the start of each period was made common knowledge to subjects (via the experimental instructions), as was the discount factor β. After all subjects clicked a button indicating they understood their beginning-of-period asset and franc positions, the first three minute trading period was begun. Subjects could post buy or sell orders for one unit of the asset at a time, though they were instructed that they could sell as many assets as they had available, or buy as many assets as they wished so long as they had sufficient francs available. During a trading period, standard double auction improvement rules were in effect: buy offers had to improve on (exceed) existing buy offers and sell offers had to improve on (undercut) existing sell offers before they were allowed to appear in the order book visible to all subjects. Subjects could also agree to buy or sell at a currently posted price at any time by clicking on the bid/ask. In that case, a transaction was declared and the transaction price was revealed to all market participants. The agreed upon transaction price in francs was paid from the buyer to the seller and one unit of the asset was transferred from the seller to the buyer. The order book was cleared, but subjects could (and did) immediately begin reposting buy and sell orders. A history of all transaction prices in the trading period was always present on all subjects' screens, which also provided information on asset trade volume. In addition to this information, each subject's franc and asset balances were adjusted in real time in response to any transactions.

3.3 Subjects, payments and timing

Subjects were primarily undergraduates from the University of Pittsburgh. No subject participated in more than one session of this experiment. At the beginning of each session, the 12 subjects were randomly assigned a role as either a type 1 or type 2 agent, so that there were 6 subjects of each type. Subjects remained in the

[12] In the event that we did not complete the final sequence by the three hour limit, we instructed subjects at the beginning of the experiment that we would bring all of them back to the laboratory as quickly as possible to complete the final sequence. Subjects would be paid for all sequences that had ended in the current session, but would be paid for the continuation sequence only when it had been completed. Their financial stake in that final sequence would be derived from at least 25 periods of play, which makes such an event very unlikely (about %1) but quite a compelling motivator to get subjects back to the lab. As it turned out, we did not have to bring back any group of subjects in any of the sessions we report on here, as they all finished within the 3-hour time-frame for which subjects had been recruited.

same role for the duration of the session. They were seated at visually isolated computer workstations and were given written instructions that were also read aloud prior to the start of play in an effort to make the instructions public knowledge. As part of the instructions, each subject was required to complete two quizzes to test comprehension of his induced utility function, the asset market trading rules and other features of the environment; the session did not proceed until all subjects had answered these quiz questions correctly. Copies of the instructions (including the quizzes) as well as the payoff tables, charts and endowment sheets used in all treatments of this experiment are available at `http://www.pitt.edu/~jduffy/assetpricing`. Subjects were recruited for a three hour session, but a typical session ended after around two hours. Subjects earned their payoffs from every period of every sequence played in the session. Mean (median) payoffs were \$22.45 (\$21.84) per subject in the linear sessions and \$18.26 (\$18.68) in the concave sessions, including a \$5 show-up payment but excluding the payment for the Holt-Laury individual choice experiment.[13] Payments were higher in the linear sessions because it was a zero-sum market (whereas social welfare was uniquely optimized in the steady-state equilibrium in the concave sessions).

At the end of each period t, subject i's end-of-period franc balance was declared his consumption level, c_t^i, for that period; the dollar amount of this consumption holding, $u^i(c_t^i)$, accrued to his cumulative cash earnings (from all prior trading periods), which were paid at the completion of the session. The timing of events in our experimental design is summarized below:

t	dividends paid: francs$=s_t^i\bar{d}+y_t^i$ assets$=s_t^i$	3-minute trading period using a double auction to trade assets and francs	consumption takes place $c_t^i=s_t^i\bar{d}+y_t^i$ $+\sum_{k_t^i=1}^{K_t^i} p_{t,k_t^i}\left(s_{t,k_t^i-1}^i - s_{t,k_t^i}^i\right)$	die role: continue to $t+1$ w.p. 5/6, else end.	$t+1$

In this timeline, K_t^i is the number of transactions completed by i in period t, p_{t,k_t^i} is the price governing the kth transaction for i in t, and $s_{t,k_t^i}^i$ is the number of shares held by i after his kth transaction in period t. Thus $s_{t,0}^i = s_t^i$ and $s_{t,K_t^i}^i = s_{t+1}^i$. Of course, this summation does not exist if i did not transact in period t; in this "autarkic" case, $c_t^i = s_t^i\bar{d} + y_t^i$. In equilibrium, sale and purchase prices are predicted to be identical over time and across subjects, but under the double auction mechanism they can differ within and across periods and subjects.

Following completion of the last sequence of trading periods, beginning with Session 7 we asked subjects to participate in a further brief experiment involving a single play of the Holt-Laury (2002) paired lottery choice instrument. The Holt-Laury paired-lottery choice task is a commonly-used individual decision-making experiment for measuring individual risk attitudes. This second experimental task was not announced in advance; subjects were instructed that, if they were willing, they could participate in a second experiment that would last an additional 10-15 minutes for which they could earn an additional monetary payment from the set $\{\$0.30, \$4.80, \$6.00, \$11.55\}$.[14] All subjects agreed to participate in this second experiment. We had subjects use the same ID number in the Holt-Laury individual-decision making experiment as they used in the 12-player asset-pricing/consumption smoothing experiment enabling us to associate behavior in the latter with a measure of each individual's risk attitudes. The instructions for the Holt-

[13] Subjects earned an average of \$7.40 for the second, Holt-Laury experiment and this amount was added to subjects' total from the asset pricing experiment.

[14] These payoff amounts are 3 times those offered by Holt and Laury (2002) in their "low-payoff" treatment. We chose to scale up the possible payoffs in this way so as to make the amounts comparable to what subjects could earn over the course of one sequence of trading periods.

Laury paired-lottery choice experiment as well as the Java program used to carry it out may be found at `http://www.pitt.edu/~jduffy/assetpricing`.

4 Experimental findings

We conducted sixteen experimental sessions. Each session involved twelve subjects with no prior experience in our experimental design (192 subjects total). The treatments used in these sessions are summarized in the table below.

Session	$\bar{d}$	$u(c)$	Holt-Laury test
1	2	concave	No
2	3	concave	No
3	2	linear	No
4	3	linear	No
5	2	linear	No
6	2	concave	No
7	3	linear	Yes
8	3	concave	Yes
9	2	concave	Yes
10	2	linear	Yes
11	3	concave	Yes
12	3	linear	Yes
13	3	linear	Yes
14	3	concave	Yes
15	2	concave	Yes
16	2	linear	Yes

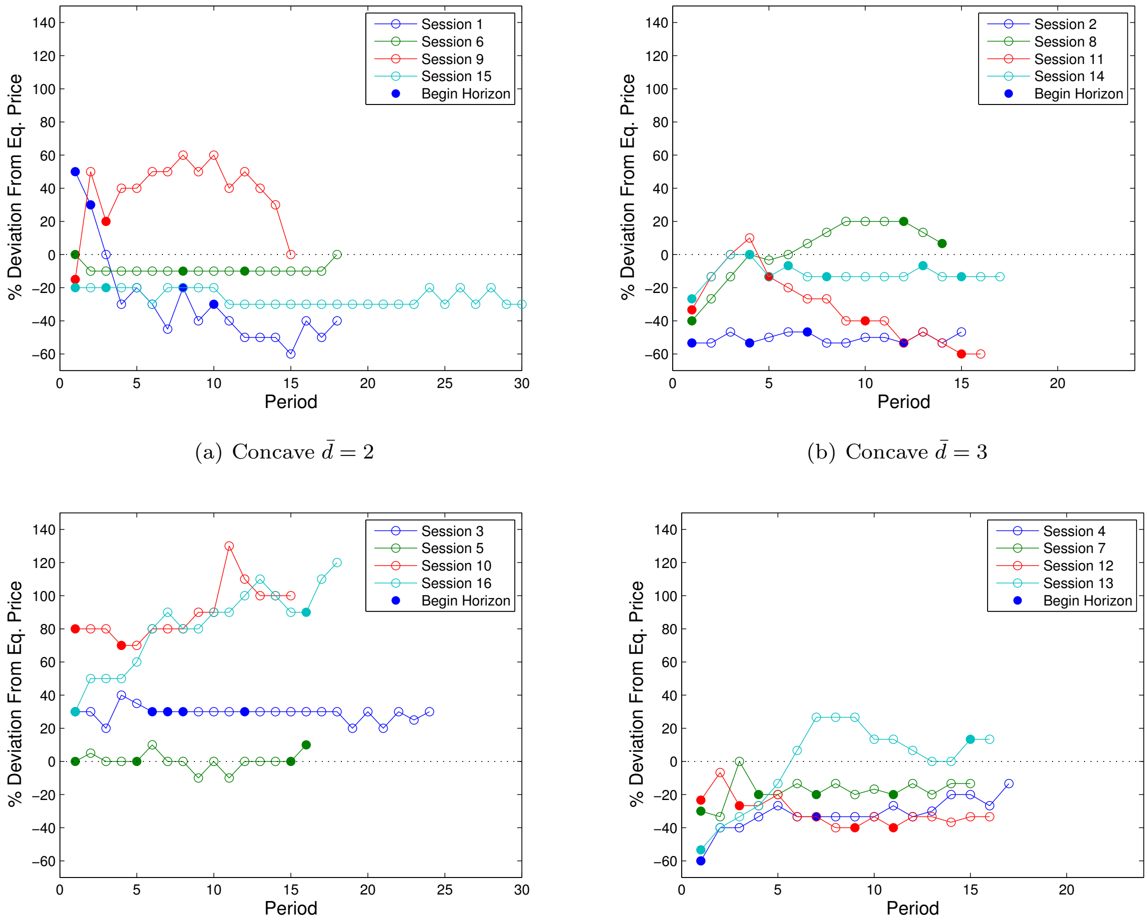
We began administering the Holt-Laury paired-lottery individual decision-making experiment following completion of the asset pricing experiment in sessions 7-16 after it had become apparent to us that indigenous risk preferences were playing an important role in our experimental findings. Thus in 10 of our 16 sessions, we have Holt-Laury measures of individual subject's tolerance for risk (120 of our 196 subjects, or 62.5%). We will henceforth refer to our four treatments as: C2, C3, L2, and L3, where C=Concave, L=Linear, and 2 or 3 refers to the dividend (d) value.

We summarize our main results as a number of different findings.

Finding 1 *In the concave utility treatment ($\phi^i < 1$), observed transaction prices at the end of the session were generally less than or equal to $p^* = \frac{\beta}{(1-\beta)}\bar{d}$.*

Figure 1 displays median transaction prices by period for all sessions. The graphs on the top (bottom) row show median transaction prices in the concave (linear) utility sessions, $\bar{d} = 2$ on the left and $\bar{d} = 3$ on the right. Solid dots represent the first period of a new indefinite trading sequence. To facilitate comparisons across sessions, prices have been transformed into percentage deviations from the predicted equilibrium price (e.g., a price of -40% in panel (a), where $\bar{d} = 2$, reflects a price of 6 in the experiment, whereas a price of -40% in panel (b), where $\bar{d} = 3$, reflects a price of 9 in the experiment).

Of the eight concave utility sessions depicted in panels (a) and (b), half end relatively close to the asset's fundamental price (7%, 0%, 0%, -13%) while the other half finish well below it (-30%, -40%, -47%, -60%). In two sessions (8 and 9) there were sustained departures above the fundamental price, but in both cases



(a) Concave $\bar{d} = 2$

(b) Concave $\bar{d} = 3$

(c) Linear $\bar{d} = 2$

(d) Linear $\bar{d} = 3$

Figure 1: Equilibrium-normalized Prices, All Sessions

the "bubbles" were self-correcting and prices finished close to fundamental value. We emphasize that these corrections were wholly endogenous rather than forced by a known finite horizon as in SSW. We further emphasize that while prices in the concave treatment lie at or below the prediction of $p^* = \frac{\beta}{(1-\beta)}\bar{d}$, subjects were never informed of this fundamental trading price (as *is* done in SSW-type asset markets). Indeed in our design, p^* must be inferred from fundamentals alone, namely β and $\bar{d}$ and a presumption that agents are forward-looking, risk-neutral expected utility maximizers.

Finding 2 *In the linear induced utility sessions ($\phi^i = 1$) trade in the asset did occur, at volumes similar to those observed in the concave sessions. Median transaction prices in the linear utility sessions are higher than median transactions prices in the corresponding concave utility sessions (same value for $\bar{d}$).*

On average, 24 shares were traded in each period of both the linear and concave sessions. However, prices (in terms of deviaations from equilbirium predictions) were much higher in the linear sessions, particularly by the end of those sessions.

Focusing on the final period of each session, we find that, on average, prices in the linear sessions were 27% higher than the predicted equilibrium price while prices in the concave sessions were 23% below the

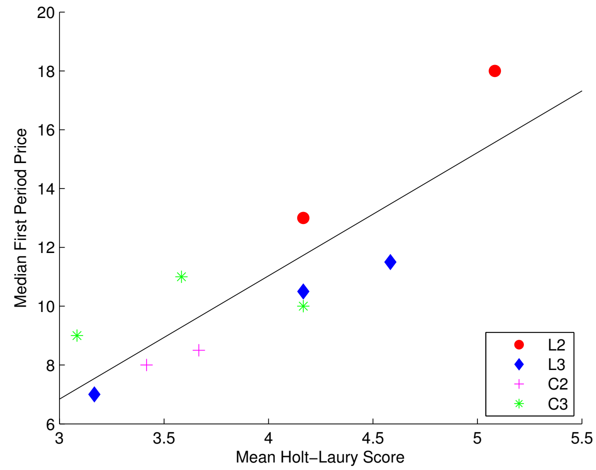


Figure 2: Influence of Indigenous Risk Preferences on Initial Prices

equilibrium price.[15] This difference is significant at the 0.0350 level. Breaking down these equilibrium-normalized prices by the four treatments, the mean final period price is 65% in L2 vs. -18% in C2, and -12% in L3 vs. -28% in C3. The difference between C2 and L2 is significant (p-value = 0.0209), the difference between C3 and L3 is not (p-value =0.5637).

There is a significant treatment effect of dividend size on deviations from equilibrium in the linear sessions (p-value = 0.0433) but not in the concave sessions (p-value = 0.5637). We offer a hypothesis and supporting evidence for this difference between the linear treatments. First, we note that the mean within-session price change was actually 1.5 times greater in L3 than in L2 (4.5 vs. 3 francs), so the difference in final equilibrium-normalized prices between L2 and L3 stems from a substantial difference in initial prices. The mean of median first period prices in L2 was 13.5 francs vs. 8.75 francs in L3; by way of comparison, the mean of median first period prices in the concave treatments were similar (10.38 in C2 and 9.25 in C3).

In the description of Finding 5 we detail our implementation of a Holt-Laury paired lottery choice, individual decision-making experiment following the gropu asset market experiment (beginning with session 7 of our design). For now we note that in this second experiment, each subject had the option to choose a high-variance or low-variance lottery at ten decision nodes, and we define a subject's Holt-Laury score as the number of high-variance lotteries chosen; the higher the Holt-Laury score, the greater is a subject's risk tolerance. In Finding 5, we report that a subject's Holt-Laury score had a significant and substantial positive influence on the number of shares he acquired in the linear, but not in the concave treatment.

Figure 2 displays the mean Holt-Laury score in a session against the median initial (first trading period) transaction price (recall that we only have Holt-Laury scores from ten sessions). The figure indicates that there is a strong positive relationship between the two; sessions with greater average risk tolerance among the

[15] We focus on transaction prices in the final period for two reasons. First, in a relatively complicated market experiment like this one there is the potential for significant learning over time. Thus prices in the final period of each session reflect the actions of subjects most experienced with the trading institution, realizations of the continuation probability, and the behavior of other subjects. Second, during the latter half of the experiment, prices in the linear sessions were either trending upward or flat, while prices in the concave sessions were trending downward or flat, so the price difference between concave and linear sessions would have likely been even greater had our experimental sessions lasted longer. Thus final period prices best reflect learning and long-term trends in these markets. If we instead take the average of the median transaction price per period during the second half of each session, the mean price across linear sessions is 21% above the fundamental price, while it is 18% below in the concave sessions. Thus the difference is still quite large, but no longer significant at the 5% level (p-value is 0.1412).

twelve subjects tend to start with a much higher mean transaction price. Indeed, a simple linear regression (using pooled data) of the median initial trading price on the Holt-Laury score yields a coefficient estimate on the latter variable of 4.19 with an associated p-value of 0.002 and R^2 of 0.73 (regression results are reported in Table 1 of the Appendix); the fitted line has been plotted in Figure 2.

We also observe that asymmetric distributions of risk tolerance between types account for most of the deviations from the fitted line; including the squared difference between a session's mean HL score and the mean HL score of its type 2 subjects brings the R^2 in the above regression up to 0.97 (the full regression result is reported in Table 1 of the Appendix). Thus it appears to be the case that the difference in prices between L2 and L3 is due entirely to the difference in the distribution of risk preferences in these sessions.[16]

Finding 3 *In the concave utility treatment, there is strong evidence that subjects used the asset to intertemporally smooth their consumption.*

Figure 3 shows the per capita shareholdings of type 1 subjects by period (the per capita shareholdings of type 2 subjects is 5 minus this number). Dashed vertical lines denote the first period of a sequence,[17] dashed horizontal lines mark equilibrium shareholdings (the bottom line in odd periods of a sequence, the top line in even periods). Recall that equilibrium shareholdings follow a perfect two-cycle, increasing in high income periods and decreasing in low income periods. As Figure 3 indicates, a two-cycle pattern (at least in sign) is precisely what occurred in each and every period on a per capita basis.[18] The two sessions with the most pronounced deviations from predicted per capita trades, sessions 8 and 9, were the sessions that produced sustained deviations above the fundamental price.

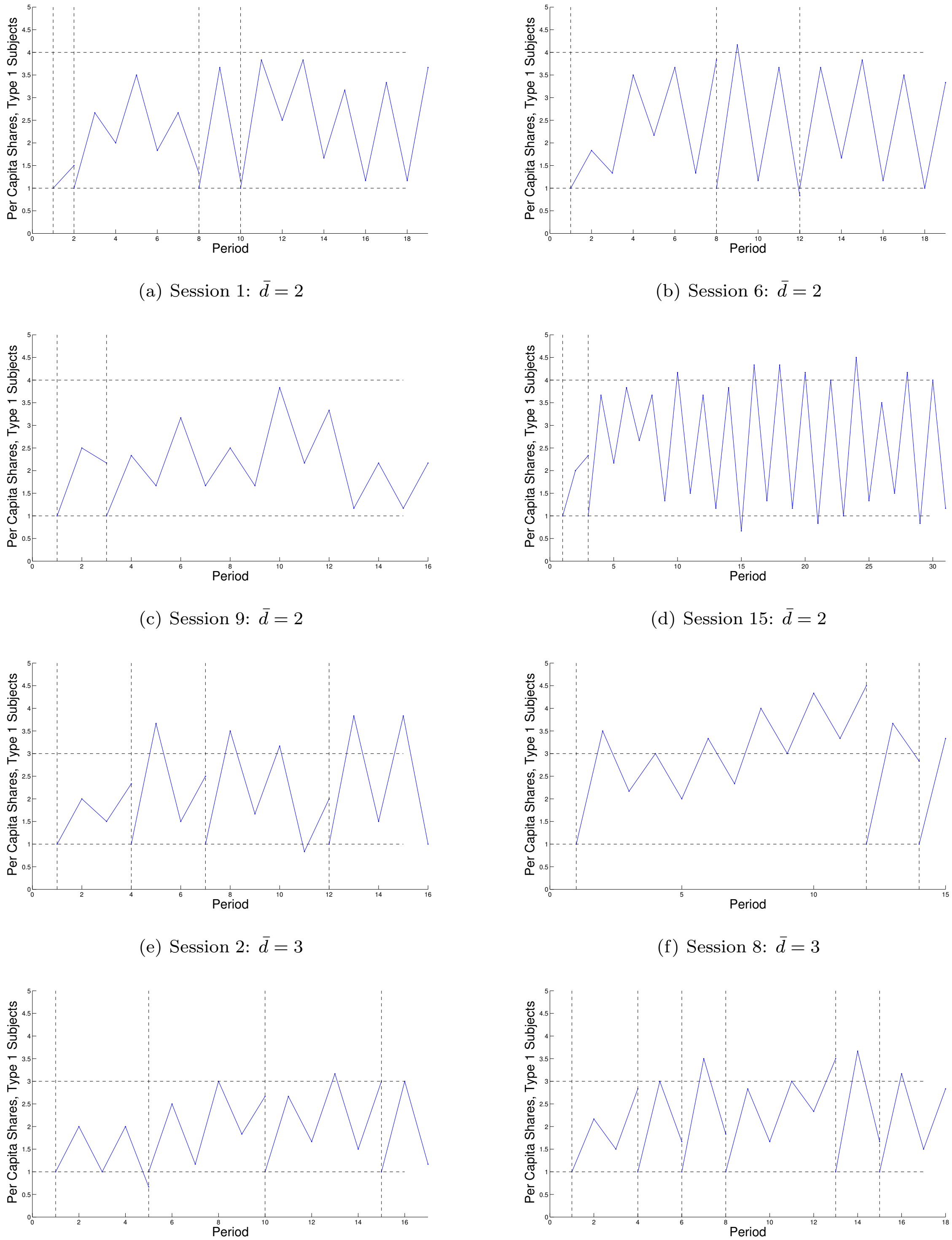
In the concave treatment sessions, type 1 subjects buy an average of 1.63 shares in odd periods (when they have high endowments of francs) and sell an average of 1.71 shares in even periods (when they have low endowments of francs). By contrast, the linear treatment sessions, type 1 subjects buy an average of just 0.28 shares in odd periods and sell and average of just 0.23 shares in even periods. Thus, while there is a small degree of consumption-smoothing taking place in the linear sessions (on a per capita basis, subjects sell shares in low income periods and buy shares in high income periods in 6 of 8 sessions), the larger magnitude of average trades in the concave sessions indicates that it is the concavity of the preference map that matters most for the smoothing of consumption observed in Figure 3 and not the cyclic income process alone.

We can also confirm a strong degree of consumption-smoothing at the individual level. Consider the proportion of periods a subject smooths consumption; that is, the proportion of periods that a type 1 (2) subject buys (sells) shares if the period is odd, and sells (buys) shares if the period is even. Figure 4 displays the cumulative distribution across subjects of this proportion, pooled by whether the session had linear or concave induced utility functions. Half of the subjects in the concave sessions smoothed consumption in at least 80% of all trading periods while just 2% of subjects in the linear sessions smoothed consumption so frequently. Nearly 90% of the subjects in the concave sessions smoothed consumption in at least half of the periods, whereas only 30% of the subjects in the linear sessions smoothed consumption that frequently. We note that the comparative absence of consumption smoothing in the linear sessions is not indicative of anti-consumption smoothing behavior. Rather, it results from the fact that many subjects in the linear treatment did not actively trade shares in many periods. It is clear from the figure that subjects in the concave sessions were actively trading in most periods, and had a strong tendency to smooth their consumption.

[16] We believe this result supports our decision to pool equilibrium-normalized prices within the linear and concave treatments and report a significant difference in median final prices between the linear and concave sessions.

[17] Since each subject begins period t with s_t^i and finishes the period with s_{t+1}^i, all vertical lines but the first also correspond to shares that were bought in the final period of the previous sequence but which expired without paying a dividend.

[18] In these figures, the period numbers shown are aggregated over all sequences played. The actual period number of each individual sequence starts with period 1, which is indicated by the dashed vertical lines.



(a) Session 1: $\bar{d} = 2$

(b) Session 6: $\bar{d} = 2$

(c) Session 9: $\bar{d} = 2$

(d) Session 15: $\bar{d} = 2$

(e) Session 2: $\bar{d} = 3$

(f) Session 8: $\bar{d} = 3$

(g) Session 11: $\bar{d} = 3$

(h) Session 14: $\bar{d} = 3$

Figure 3: Shares in Concave Utility Sessions

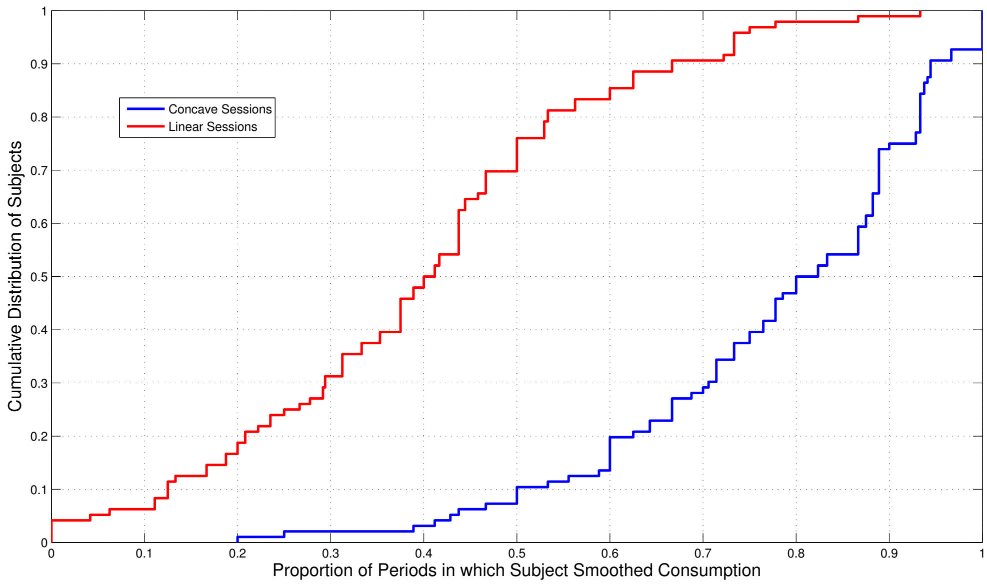


Figure 4: Individual Consumption-Smoothing

As noted in the introduction, the experimental evidence on whether subjects can learn to consumption-smooth in an optimal manner (without tradeable assets) has not been encouraging; by contrast, in our design where subjects must engage in trade in the asset to vary their savings across periods, consumption-smoothing seems to come rather naturally to most subjects.

Finding 4 *In the linear utility treatment, the asset was hoarded by just a few subjects.*

In the linear treatment subjects have no induced motivation to smooth consumption and thus no induced reason to trade at p^* under the assumption of risk neutrality. However, we observe substantial trade in these sessions, with roughly half of the subjects selling nearly all of their shares, and a small number of subjects accumulating most of the shares. Figure 5 displays the cumulative distribution of mean individual shareholdings during the final two periods of the final sequence of each session, aggregated according to whether the treatment induced a linear or concave utility function.[19] We average across the final two periods due to the consumption-smoothing identified in Finding 3; use of final period data would bias upward the shareholdings of subjects in the concave sessions. We consider the final two periods rather than averaging shares over the final sequence or over the entire session because it can take several periods within a sequence for a subject to achieve a targeted position due to the budget constraint. Forty-three percent of subjects in the linear sessions held an average of 0.5 shares or less during the final two periods. By contrast, just 9% of subjects in the concave session held so few shares during the final two periods. At the other extreme, 16% of subjects in the linear sessions held an average of at least 6 shares during the final two periods, while only 4% of subjects in the concave sessions held so many shares. Thus subjects in the linear sessions were five times more likely to hold 'few' (< 1) shares and four times more likely to hold 'many' (≥ 6) shares as were subjects in the concave sessions, while subjects in the concave sessions were more than twice as likely to hold an intermediate quantity $\in (1, 6)$, of shares (87% vs. 41%).

[19] We use the final sequence with a duration of at least two periods.

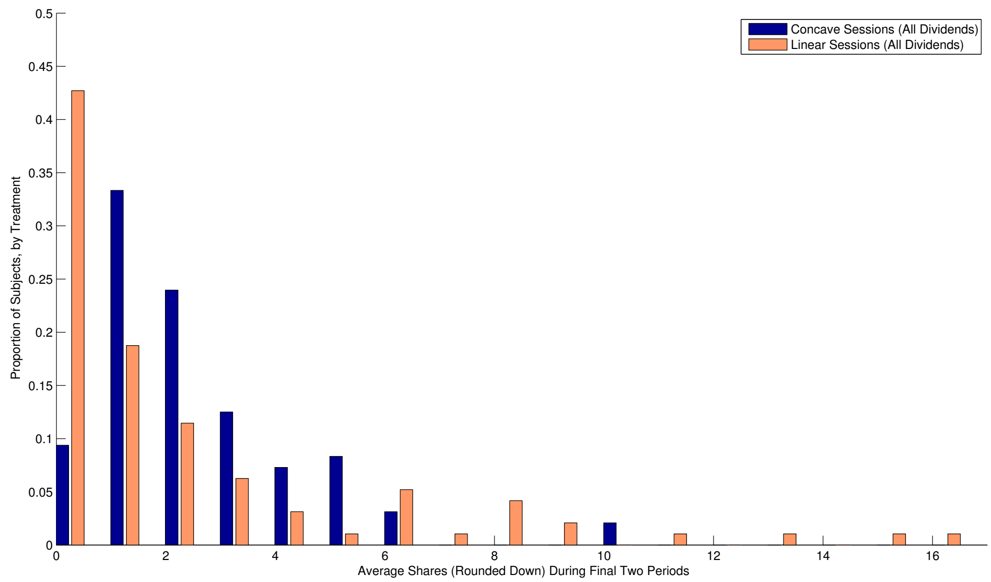


Figure 5: Distribution (by Treatment) of Mean Shareholdings During the Final Two Periods

A useful summary statistic for the distribution of shares is the Gini coefficient, a measure of inequality that is equal to zero when each subject holds an identical quantity of shares and is equal to one when one subject owns all shares. Under autarky, where subjects hold their initial endowments (1/2 hold 1 share, the other 1/2 hold 4 shares), the Gini coefficient is 0.3. In the consumption-smoothing equilibrium of the Concave utility treatment, the Gini coefficient when $d = 2$ (treament C2) is the same as under autarky: 0.3. When $d = 3$, (treatment C3), the Gini coefficient (over two periods) is slightly lower at 0.25. We find that the mean Gini coefficient for mean shareholdings in the final two periods of all concave sessions is 0.37. By contrast, the mean Gini coefficient for mean shareholdings in the final two periods of all linear sessions is significantly larger, at 0.63; (Mann-Whitney test, p-value 0.0008). This difference largely reflects the hoarding of a large number of shares by just a few subjects in the linear treatment, behavior that was absent in the concave treatment sessions.

Indeed, an interesting regularity is that exactly two of twelve (16.67%) subjects in each of the 8 linear sessions held an average of at least 6 shares of the asset during the final two trading periods. As there is a total of just 30 assets in each session of our design, these two subjects held an average of *at least* 40% of all asset shares in a session. Thus the subjects identified in the right tail of the distribution in Figure 5 were divided up evenly across the 8 linear sessions. The actual proportion of shares held by the largest two shareholders during the final two periods averaged 61% across all linear sessions, compared with just 38% across all concave sessions. Applying the Mann-Whitney rank sum test, the distribution of shares held by the largest two shareholders in the linear sessions is significantly larger than the same distribution found in the concave sessions (p-value = 0.0135). To benchmark these statistics, under autarky the two largest shareholders would hold 27% (8/30) of the shares in all sessions. If subjects in the C2 (C3) treatment coordinated on the risk-neutral steady state equilibrium, 17% (20%) of the shares would be held by the two largest shareholders on average during the final two periods.

Finding 5 *In the linear sessions there is a strong and significant positive relationship between a subject's* *number of high-variance choices in the Holt-Laury paired lottery choice task (a measure of risk tolerance) and the subjects' end-of-session shareholdings. There is no such relationship in the concave sessions. In the concave sessions there is a significant negative relationship between a subject's distance from indigenous risk-neutral preferences and the expected value of his net transactions, There is no such difference in the linear sessions. Thus risk-neutral subjects tend to make the most sound trading decisions in the concave sessions, but get "caught up" in the pricing bubbles of the linear sessions.*

After running the first six sessions of this experiment it became apparent to us that the indigenous risk preferences of subjects were a substantial influence on asset prices and the distribution of shareholdings, particularly in the linear sessions. Intuitively, over the course of a linear session sequence the price of the asset will be bid up by subjects with the highest risk tolerance, causing shareholdings to become concentrated among these subjects. Thus, beginning with session 7 we had subjects participate in a second experiment, involving the Holt-Laury paired lottery choice instrument. As discussed earlier (in section xx) this second experiment occurred *after* the asset market experiment had concluded and was not announced in advance. In this second experiment, subjects faced a series of ten choices between two lotteries, each paying either a low or high payoff; one lottery, choice A, had a low variance between the two payoffs while the other lottery, choice B, had a higher variance between the two payoffs. For choice $n \in \{1, 2, ..10\}$, the probability of getting the high payoff in the chosen lottery was $(0.1)n$. One of the choices was selected at random after all lottery choice decisions had been made, that lottery was played (with computer-generated probabilities), and the subject was paid according to the outcome. As detailed in Holt and Laury (2002), a risk-neutral expected utility maximizer should choose the high-variance lottery B six times. We refer to a subject's *HL score* as the number of times he selected the high-variance lottery B. The mean HL score in the final nine sessions was 3.9. Roughly 16% of the subjects had an HL score of at least 6, and 30% had a score of at least 5, a distribution reasonably consistent with the experimental literature for lotteries of this scale.

For pooled linear and concave treatments, we ran a random effects regression of HL scores on average shareholdings during the final two periods of each session. This specification was necessary since the distribution of HL scores in each session was endogenous (e.g., a subject with an HL score of 6 might be the least risk-averse subject in one session but only the third least risk-averse in another). In the linear case, the estimated coefficient on the HL score was 0.46 and its associated p-value was 0.033 (the full regression results are presented in Table 2 of the Appendix). Thus the model predicts that for every two additional high-variance choices in the Holt-Laury lottery choice experiment, a subject will hold nearly one additional share of the asset by the end of the period. This is a large impact, as there are only 2.5 shares per capita in these economies. On the other hand, in the concave case the estimated coefficient on the HL score is -0.10 with an associated p-value of 0.407 (full results are reported in Table 3). The estimated coefficients and p-values in these regressions are nearly identical to those in the analogous fixed effects regressions. Thus, we find that the HL score is a useful predictor of final shareholdings only in the linear sessions: The more risk-tolerant a subject was relative to his session cohort, the more shares he tends to own by the end of a linear-treatment session.

For further corroboration of this result, we considered the Holt-Laury rank of the two largest shareholders during the final two periods of the session. The rank, in terms of final shareholdings (1=lowest, 12=highest) of the subject with the highest HL score is 12, the rank of the subject with the second-highest HL score is 11, and so on. Ties are assigned the average position within the tie; e.g., if the second-highest score is 6 and it is shared by two subjects, each of them is assigned a rank of 10.5. The mean Holt-Laury score for the two "hoarders" in each session (as described in Finding 4) is 8.3, and their median rank in terms of shareholdings is 10.5. The probability that the average rank of the two hoarders across five sessions is at least 8.3 if they are drawn at random from the distribution of Holt-Laury scores observed in our experiment is bounded from above by 0.047,[20] which further confirms the strong relationship between shareholdings and the relative size of the HL score within-session.

Finally, we consider the relationship between a subjects' HL score and the expected value of a subject's net transactions. For subject i in period t, let h_t^i be his net shares acquired and f_t^i be his net francs acquired. Recalling that p^* is the fundamental price, let $v_t^i = f_t^i + h_t^i p^*$. Thus v is the net change in expected value of the subject's asset and cash position during the trading period. Consider first, behavior in the linear sessions. A subject who is risk neutral with regard to expected monetary payoffs should always take a positive expected value position; that is, if actual transaction prices are below the fundamental price the risk-neutral subject should choose to be a buyer, and if the price is above the fundamental price, that same subject should choose to be a seller. What about non-risk neutral subjects? We will consider such types more formally in the following section, but intuitively, for prices below the fundamental price, we expect that both risk-neutral and risk-seeking subjects will take positive expected value positions while risk-averse subjects may potentially take negative expected value positions depending on the price and their degree of risk-aversion. Similarly, for prices above the fundamental price, we expect risk-neutral and risk-averse subjects to take positive expected value positions while risk-seeking subjects may potentially take negative expected value positions. Thus during a session with exposure to a wide range of prices, we should expect a risk-neutral subject to take a higher expected value position relative to other subjects in his session. The further a subject's preferences are from the risk neutral benchmark, the lower should be his expected value position.

For the concave sessions, because most subjects are consumption-smoothers we have to adjust for the fact that there are generally more odd periods than even periods. We do this by calculating v separately for odd and even periods, taking the period average of each, adding them together and dividing by two. This gives us the mean net addition to expected value for a subject in each period. We run a quadratic random effects regression of the HL score on the mean net expected value function for the concave sessions (regression results reported are in Table 4 in the Appendix). The coefficient on the HL score is 2.08 (p-value 0.012) and the coefficient on the squared HL term is -0.195 (p-value 0.029). Thus the fitted curve is concave in the HL score as we would expect, and has a peak at an HL score of 5.3, which is nearly risk-neutral. Running this model for the linear sessions we get much smaller and highly insignificant coefficients (see Table 4).

Thus it appears to be the case that risk-neutral subjects take net positions of greater expected value than other subjects in the concave sessions. They also tend to earn more than other subjects, as is apparent in Figure 6 (the maximum of the fitted curve is for an HL score of 5.7; regression results are reported in Table 6), so the net increases in expected value are not coming at the expense of consumption-smoothing. The farther a subject's risk tolerance departs from the risk-neutral benchmark, the lower the expected value of his net positions. However, this result does not carry over to the linear sessions. In fact, earnings are decreasing in HL scores in these sessions, although the difference is small. Risk-neutral subjects are among the most risk-tolerant subjects in these sessions, so naturally they tend to accumulate shares over the course of these sessions. But they often get caught up in a "bubble" as they compete with other risk-tolerant subjects for shares of the asset.

5 Indigenous (homegrown) risk preferences

It is not a simple task to even define optimal behavior for non-risk-neutral expected utility maximizers in this experiment. Beyond the difficulty of structuring subjects' expectations about future prices, it is not

[20] This computation assumes there are no ties in Holt-Laury rank, which of course is not possible with twelve subjects and only 10 possible HL scores. If one of the hoarders is tied with another subject in HL score it pulls his rank downward.

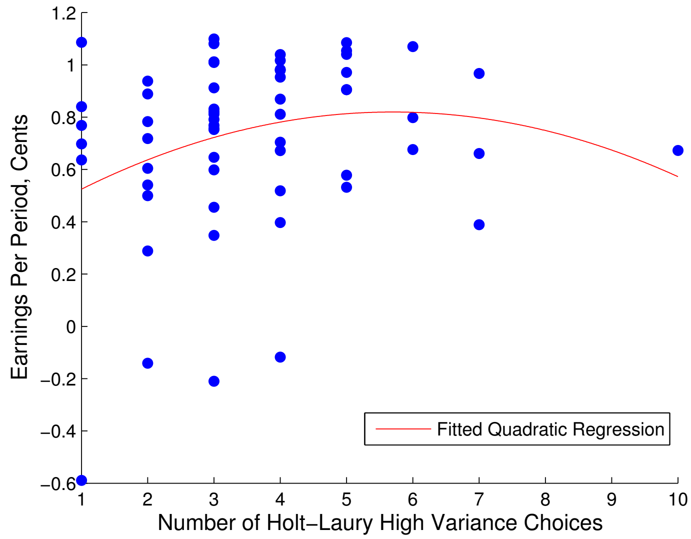


Figure 6: Earnings in the Concave Sessions by Holt-Laury Score

clear what is the best way to deal with wealth effects. As Rabin (2000) points out, the degree of risk-aversion exhibited by subjects over small stakes in laboratory settings cannot be rationalized by lifetime expected utility optimization because it would imply an implausibly high degree of risk-aversion in high stakes lotteries; it follows that most rational subjects should behave as risk netural expected utility maximizers in the lab. If the subjects we have identified (via the HL test) as risk-averse do not maximize expected utility over all decisions (both inside and outside the lab), should we nevertheless expect them to maximize expected utility over a sequence of decisions within the lab?[21]

We first describe how a non-risk-neutral subject should behave in the final period of a session. Let $m_t = u(c_t)$ and $M_t = \sum_{s=0}^{t} m_s$ be the sum of dollars a subject has earned through period t of the current sequence, given initial wealth m_0. This initial wealth level, m_0, is unknown, so we treat it generally; it may equal zero or include some combination of the promised show-up fee, cumulative earnings within or across sequences, or even an individual's own wealth outside of the laboratory. Superscripts indexing individual subjects are suppressed for notational convenience. Let $v(m)$ be a subject's indigenous utility over m dollars, and suppose this function is strictly concave, strictly monotonic, and twice differentiable. Then the subject's expected value of participating in the current sequence is

$$V = \sum_{t=1}^{\infty} \beta^{t-1} (1-\beta) v(M_t) . \tag{6}$$

The sequence $\langle s_t \rangle_{t=2}^{\infty}$ is the control used to adjust V. The first order conditions for V with respect to s_{t+1} for $t \geq 1$ can be written as:

$$u'(c_t) p_t \sum_{s=t}^{\infty} \beta^{s-t} E_t\{v'(M_s)\} = \sum_{s=t}^{\infty} \beta^{s-t+1} E_t\{v'(M_{s+1}) u'(c_{t+1}) (d + p_{t+1})\} \tag{7}$$

To aid in understanding the choices of rational, risk-averse subjects in our experiment, let us assume, for simplicity that subjects have myopic expectations with respect to future prices; in particular, each subject

[21] Benjamin, Brown, and Shapiro (2006) report that small stakes risk-aversion is negatively correlated with cognitive ability, further casting doubt on the likelihood that risk-averse subjects are dynamic expected utility optimizers.

expects the price in all future periods to equal the current price with probability one. (In equilibrium this would be true, of course). Under this assumption, the subject's first-order condition reduces to:

$$p = \frac{d}{\frac{u'(c_t)}{u'(c_{t+1})}\left(1 + \frac{v'(M_t)}{\sum_{s=t}^{\infty} \beta^{s-t+1} v'(M_{s+1})}\right) - 1} \tag{8}$$

Notice the similarity of (8) to (2). This is not a coincidence; if indigenous risk preferences are linear, the indigenous marginal utility of wealth is constant, and applying a little algebra to (8) produces (2). This justifies our earlier claim that the infinite horizon economy and its stochastic horizon economy analogue share the same steady-state equilibrium provided that subjects are risk-neutral.

5.1 Induced Linear Preferences

We begin with the case where induced utility is linear (that is, treatments L2 and L3), so $u(c) = \alpha c$. Then by (8) prices can be constant only if $v'(M_{t+1}) = kv'(M_t)$ for all t, where $k \in (0, 1)$ is a constant rate of decay of marginal utility. Thus (8) reduces to

$$p = \frac{k\beta}{1 - k\beta}\bar{d}. \tag{9}$$

Suppose subjects have indigenous CRRA utility, i.e., $v(m) = \frac{1}{1-\gamma}m^{1-\gamma}$, where $\gamma \in (0, 1)$. Then $k = \left(\frac{M_t}{M_{t+1}}\right)^{\gamma}$. Substituting this expression into (9) and applying some algebra, we obtain the condition $M_{t+1} = gM_t$, where $g = \left[\frac{(\bar{d}+p)\beta}{p}\right]^{\frac{1}{\gamma}}$ is the optimal growth rate of wealth in period 2 forward. If $p = p^*$ then $g = 1$, so consumption is zero after the first period at the interior solution. Since we assume subjects cannot borrow against future income, a risk-averse subject facing constant price p^* thus adopts the corner solution in which he sells all of his assets in the first period and simply consumes his income in subsequent periods (this is also true for $p > p^*$, in which case $g < 1$).

For $p < p^*$ we have $g > 1$, so the subject prefers that his wealth grows over time at a constant rate. This growth rate is decreasing in the risk-aversion of the subject and price. Thus a more risk-averse subject facing higher prices prefers more of his earnings in the sequence up-front and accumulates wealth at a slower rate. For all $\gamma > 0$ wealth eventually explodes as the curvature of the subject's utility function becomes approximately linear at "high" levels of consumption; that is, the subject behaves almost risk-neutrally once he's accumulated sufficient wealth, and would prefer to go long on assets at the current price if he were allowed to borrow. Note that it is not possible for all subjects to behave as expected utility maximizers at a constant price, because aggregate income in the experiment is constant in each period. Eventually demand will outpace supply, causing prices to rise towards p^*.

How quickly should we expect excess demand to rise? Consider the behavior of a subject with $\gamma = 0.5$ in an L3 session who faces constant price $p = 10$ (note $\gamma = 0.5$ is the mean estimated degree of risk-aversion in our experiment, and $p = 10$ was a commonly observed and fairly stable price in two of our four L3 sessions). Suppose the subject considers initial wealth m_0 to be his show-up fee, \$5. In the upper-left panel of Figure 7 is displayed the optimal shareholdings for this subject. Regardless of type this subject will spend all francs on shares in the first three periods. Thus shareholdings at the end of the first period should be more than 12 if the subject is a type 1 or more than 7 if he is a type 2; excess demand for a pair of subjects with a mean degree of risk-aversion will be four times their shareholdings at the end of the first period alone!

The upper-right panel of Figure 7 reveals that optimal behavior is clearly sensitive to the choice of initial wealth, but even if the initial wealth reference level is \$0, by the end of the fifth period a pair of subjects with an average degree of risk-aversion will have excess demand nearly four times their initial shareholdings.

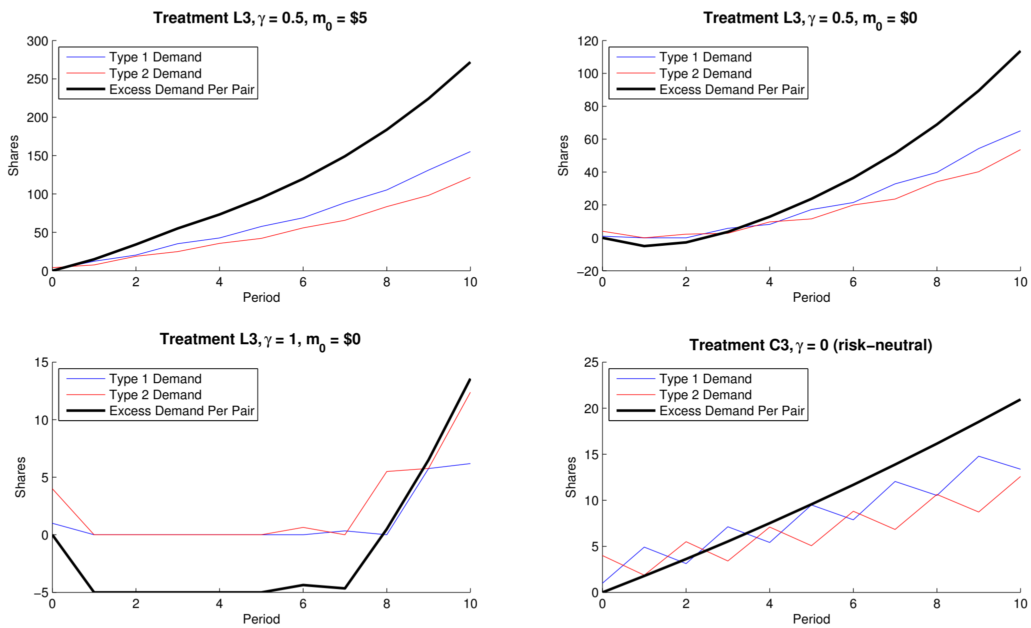


Figure 7: Optimal Behavior Under Constant Price $p = 10$

A highly risk-averse subject with no initial wealth, represented in the lower-left panel of the figure, will take longer to ramp up share growth. While the non-constant prices available in the experiment greatly complicate the analysis of optimal behavior, it seems unlikely that most subjects in the linear sessions attempted to dynamically optimize expected utility when prices were below p^*.[22]

What if risk-averse subjects ignore wealth effects entirely, even within a sequence? It is clear that most subjects ignore or under-weight wealth outside of the lab when making decisions in an experiment, so postulating that subjects ignore wealth earned within a session or sequence is certainly plausible. In that case, we can consider holding an asset at any point in time as a compound lottery. For a subject with $\gamma = 0.5$, the certainty equivalent of this compound lottery when $\bar{d} = 3$ is about 10.4 francs (recall the expected value of this compound lottery is 15 francs). Thus a subject with a mean degree of small-stakes risk aversion who ignores wealth effects should be nearly indifferent to buying or selling shares at the lowest prices observed after the first period of the L3 sessions, while he should sell the asset at higher prices. Therefore myopic risk-aversion can rationalize the fact that most subjects sell off their shares even when prices are well below the fundamental price in sessions 4, 7, and 12, while dynamic optimization of expected utility implies that some of these subjects should have re-entered the market as buyers later in the session, pushing prices higher.

5.2 Induced Concave Preferences

In the lower-right panel of Figure 7 we observe optimal shareholdings for a subject who is indigenously risk-neutral and faces a constant price of 10 in a C3 session. Desired shareholdings increase over time since $p < p^*$, but the rate of increase is much slower than for a rationally risk-averse subject at the same price in an L3 session. Thus while the risk-neutral steady state equilibrium price of comparable linear and concave

[22] We are presently conducting a new stochastic horizon study where subjects can trade in a "perfectly competitive" market as much as they like at a constant price, which will provide a rigorous test of this hypothesis.

economies is the same, optimal behavior out of equilibrium is distinctly different in the two cases. For linear induced preferences subjects are typically at a corner outcome due to budget or total resource constraints, preferring to buy or sell as many shares as they can. Further, for risk-averse subjects the transition from being a corner seller to a corner buyer happens very quickly. This knife-edge feature of induced linear preferences is robust to an intuitive behavioral strategy where wealth effects are ignored. For concave induced preferences consumption-smoothing remains a strong feature of optimal behavior out of equilibrium. This is apparent for the risk-neutral agent represented in the lower-right panel of Figure 7, but it is intuitively true for risk-averse agents, as well. While equation (8) has proven difficult to solve numerically, intuitively a risk-averse agent facing a constant price should hold fewer shares initially and increase shareholdings at a slower rate than a risk-neutral agent facing the same price.

As in the the case of induced linear preferences, there is an intuitive behavioral strategy for concave induced preferences in which subjects ignore wealth effects. Suppose subjects myopically equate the expected marginal cost of a trade with its expected marginal benefit. Thus a type 1 subject in the first period of a sequence would equate the marginal cost of buying Δ shares at price p in the current period with the expected marginal benefit of those shares in the subsequent period (these shares return a dividend plus the option value of re-sale). Assuming CRRA utility, the subject would choose Δ such that:

$$\left[\frac{\delta+\alpha\left(y_2+s_1 d+\Delta(d+p)\right)^{\phi}}{\delta+\alpha\left(y_1+s_1 d-\Delta p\right)^{\phi}}\right]^{\gamma}=-\frac{\beta(d+p)}{p}\left[\frac{y_2+s_1 d+\Delta(d+p)}{y_1+s_1 d-\Delta p}\right]^{\phi-1} \tag{10}$$

The equation for a type 2 agent is similar, except this subject would set the marginal benefit of selling shares in the current period equal to the expected marginal cost in the subsequent period.

Suppose $d=3$. At the steady-state equilibrium price of 15, all subjects following this strategy prefer to buy two shares in high income periods and sell two shares in low income periods regardless of their degree of risk-aversion; that is, these subjects would be observationally equivalent to risk-neutral optimizers. If $p=10$, a risk-neutral type 1 subject following this behavioral strategy will prefer to purchase 3 shares in the first period and sell 2.78 shares in the second period. Thus he still has a preferences to increase his shareholdings over time, but at a much slower rate than a risk-neutral optimizer. In fact, because shares are discrete, the subject would simply prefer to cycle between buying and selling three shares. Interestingly, myopic behavior is nearly identical regardless of degree of risk-aversion in a continuous economy, and identical in a discrete economy. For example, a type 1 subject with $\gamma=1$ (a very risk-averse subject) would prefer to buy 2.94 shares in the first period and sell 2.81 shares in the second period. Behavior for type 2 subjects is very similar, except they would sell shares in odd periods and buy shares in even periods. Therefore, if subjects follow this behavioral strategy all prices we observe in the concave sessions are sustainable as equilibria. It is only if prices get too low (around 60% below p^*) that we should expect to see the least risk-averse subjects accumulate shares over time.

Because prices are endogenous and typically vary within-session in our experiment, our design is ill-suited to identify individual strategies used by subjects in the experiment. Our goal in this section is to make it clear that optimal behavior out of equilibrium, under the simplifying assumption of constant prices, is very different between the linear and concave treatments, and this difference is robust to intuitive behavioral deviations from dynamic optimization of expected utility within the lab. Optimal behavior for linear induced preferences has a knife-edge quality: Nearly every subject at nearly any price should either buy or sell as many shares as are available. Findings 4 and 5 are consistent with this prediction; most subjects sell most of their shares while a small fraction buy nearly all of the shares available. Those who buy tend to be the least risk-averse subjects in the session as identified by the Holt-Laury paired choice lottery. Optimal behavior for concave induced preferences is characterized by thick markets where everyone buys or sells shares in every period, a characterization consistent with Finding 3. Further, while individual behavior should quickly push prices to at least p^* very quickly in the case of linear induced preferences, low prices are consistent with "reasonable" behavior in the case of concave induced preferences.

6 Conclusion

Our research design provides an important bridge between the literature on experimental methods and experimental asset pricing models, and the literature on equilibrium asset pricing models used by macroeconomic/business cycle and finance researchers. To date there has been little communication between these two fields. Our work integrating methods and models from both fields will enable both literatures to speak to a broader audience.

What we learn from our experimental design integrating these segmented literatures is that an induced incentive to consumption-smooth can serve as a powerful brake on asset prices. If we very loosely define a bubble as a sustained deviation above an asset's fundamental price, half of our laboratory economies with no induced incentive to trade (linear utility treatment) experienced bubbles, and in three-quarters of those sessions the bubble exhibited no signs of collapse. Indeed, in half of the sessions exhibiting bubbles, the median price of the asset towards the end of the experiment was more than double the fundamental price and was continuing to rise. In contrast, when consumption-smoothing was induced (concave utility treatment) in an otherwise identical economy, bubbly prices were observed in only one-quarter of sessions and in these sessions the median price of the asset had collapsed to the fundamental price by the (random) end of the experimental session. Thus price bubbles were less frequent, of lesser magnitude, and of shorter duration when we induced consumption-smoothing in an otherwise identical economy.

These results may offer some preliminary guidance as to which naturally occurring markets are most prone to experience large asset price bubbles. We might reasonably expect that markets with a high concentration of speculators are the most likely to bubble, while markets with a large number of participants who trade at least in part on the basis of intrinsic preferences are less likely to do so (in our study market depth itself appears to be a function of what motivates agents to trade). Of course in our current design we do not observe economies with mixtures of intrinsic and non-intrinsic participants, so at this point we merely offer the possibility that laboratory experiments may provide the basis for such a characterization in the future.

We anticipate that our basic research design can be extended in at least three distinct directions. First, the design can be moved a step closer to the environments used in the macrofinance literature; specifically, by adding a Markov process for dividends, and/or a known, constant growth rate in endowment income. The purpose of such treatments would be to explore the robustness of our present findings in the deterministic setting to stochastic or growing environments. A further step would be to induce consumption-smoothing through overlapping generations rather than via cyclic income and a concave exchange rate; how would a finite horizon at the individual subject level (while maintaining an indefinite horizon at the market level) impact asset prices?

In another direction, it would be useful to clarify the impact of features of our experimental design relative to the much-studied experimental design of Smith, Suchanek, and Williams (1988). For example, one could study a finite horizon, lump-of-money, linear (induced) utility design as in SSW, but where there exists a constant probability of firm bankruptcy as in our present design. Would the interaction of a finite horizon and firm bankruptcy inhibit bubbles relative to the SSW design, or is an induced economic incentive to trade necessary to prevent a small group of speculators from effectively setting asset prices across a broad range of economies?

Finally, it would be interesting to design an experiment to rigorously test for within-session risk-preferences and wealth effects. In our present design we observe little evidence that risk-averse subjects (classified by the Holt-Laury paired choice lottery instrument) attempt to increase their shareholdings over time in the linear induced utility treatment in sessions where prices are relatively constant, a contradiction of time-consistent rational risk aversion. This result is perhaps not surprising; if subjects exhibit a different degree of risk aversion in small stakes laboratory gambles than they apply to 'large' economic decisions (i.e., the Rabin (2000) critique), then perhaps it should be expected that they exhibit myopic risk aversion over a sequence of small stake gambles rather than maximize expected utility globally over the sequence. To our knowledge this hypothesis has not been directly tested. In fact, most laboratory studies of risk preferences explicitly eliminate the possibility of laboratory wealth effects on subject behavior. Modifying our present design, subjects could face a sequence of decisions to buy or sell assets directly with the experimenter at a constant price with a constant risk of bankruptcy, i.e., we can study individual risk preferences in a stationary, competitive market. Will risk-averse subjects (as identified by the HL test instrument) tend to increase their shareholdings as their earnings in the experiment accumulate, as dictated by CRRA preferences, or will their decisions be more myopic? This is an important question, because empirical macroeconomic studies are often calibrated to a distribution of CRRA preferences commonly estimated in laboratory studies. Our present paper suggests the possibility that the wealth effects implied by CRRA utility are not observed for many subjects. While CRRA seems to fit laboratory data on static decisions reasonably well (for a given magnitude of the stakes involved), it is possible that an alternative model of risk-aversion is needed for dynamic decisions. The relationship of dynamic financial decision-making to a subject's elicited (static) degree of risk aversion has the potential to lead to many new and exciting findings.

References

Asparouhova, Elena, Peter Bossaerts, and Charles R. Plott (2003), "Excess Demand and Equilibration in Multi-Security Financial Markets: The Empirical Evidence," *Journal of Financial Markets* 6, 1-21.

Ballinger, T. Parker, Michael G. Palumbo and Nathanial T. Wilcox (2003), "Precautionary Savings and Social Learning Across Generations: An Experiment," *Economic Journal* 113, 920-947.

Benjamin, Daniel, Sebastian Brown, and Jesse Shapiro (2006), "Who is 'Behavioral'? Cognitive Ability and Anomalous Preferences," mimeo.

Bossaerts, Peter and Charles R. Plott (2002), "The CAPM in thin experimental financial markets," *Journal of Economic Dynamics and Control* 26, 1093-1112.

Bossaerts, Peter Charles R. Plott and William R. Zame (2007), "Prices and portfolio choices in financial markets: Theory, econometrics, experiments," *Econometrica* 75, 993-1038.

Breeden, Douglas T. (1979), "An intertemporal asset pricing model with stochastic consumption and investment opportunities," *Journal of Financial Economics* 7, 265–296.

Camerer, Colin and Keith Weigelt (1993), "Convergence in experimental double auctions for stochastically lived assets," in D. Friedman and J. Rust, Eds., *The Double Auction Market: Institutions, Theories and Evidence* Cambridge, MA: Perseus Publishing, 355-396.

Carbone, Enrica and John D. Hey (2004), "The Effect of Unemployment on Consumption: An Experimental Analysis," *Economic Journal* 114, 660-683.

Cochrane, John H. (2005), *Asset Pricing*, Revised Edition. Princeton: Princeton University Press.

Dufwenberg, Martin, Tobias Lindqvist, and Evan Moore (2005), "Bubbles and experience: An experiment," *American Economic Review* 95, 1731-37.

Fischbacher, Urs (2007), "z-Tree: Zurich toolbox for ready-made economic experiments," *Experimental Economics* 10, 171-178.

Forsythe, Robert, Thomas Palfrey and Charles R. Plott (1982), "Asset valuation in an experimental market," *Econometrica* 50, 537-567.

Friedman, Daniel, Glenn Harrison and Jon Salmon (1984), "The informational efficiency of experimental asset markets," *Journal of Political Economy* 92, 349-408.

Hansen, Lars P., and Kenneth J. Singleton (1983), "Stochastic consumption, risk aversion and the temporal behavior of asset returns," *Journal of Political Economy* 91, 249-265.

Harrison, Glenn W., Morten I. Lau, Elisabet E. Rutstrom, and Melanie B. Sullivan, "Eliciting risk and time preferences using field experiments: Some methodological issues," in J. Carpenter, G.W. Harrison, and J.A. List (eds.), *Field Experiments in Economics* (Greenwich, CT: JAI Press, Research in Experimental Economics, Volume 10, 2005).

Haruvy, Ernan, Yaron Lahav and Charles N. Noussair (2007), Traders' expectations in asset markets: Experimental evidence. *American Economic Review*, 97, 1901-1920.

Hey, John D. and Valentino Dardanoni (1988), "Optimal consumption under uncertainty: An experimental investigation," *Economic Journal* 98, 105-116.

Holt, Charles A., and Susan K. Laury (2002), "Risk aversion and incentive effects in lottery choices," *American Economic Review* 92(5), 1644-1655.

Holt, Charles A., and Susuan K. Laury (2005), "Risk aversion and incentive effects: New data without order effects," *American Economic Review* 95(3), 902-912.

Hussam, Reshmaan N., David Porter, and Vernon L. Smith "Thar she blows: Can bubbles be rekindled with experienced subjects?" *American Economic Review* 98(3), 924937.

Kocherlakota, Narayana R. (1996), "The equity premium: It's still a puzzle," *Journal of Economic Literature* 34, 42-71.

Lei, Vivian, Charles N. Noussair and Charles R. Plott (2001), "Nonspeculative bubbles in experimental asset markets: Lack of common knowledge of rationality vs. actual irrationality," *Econometrica* 69, 831–59.

Lengwiler, Yvan (2004), Microfoundations of Financial Economics, Princeton: Princeton University Press.

LeRoy, Stephen F. and Richard D. Porter (1981), "The present value relation: Tests based on implied variance bounds," *Econometrica*, 49, 555—574.

Lucas, Robert E. Jr., (1978), "Asset prices in an exchange economy," *Econometrica* 46, 1429–1445.

Lugovskyy, Volodymyr, Daniela Puzzello, and Steven Tucker (2010), "An experimental study of bubble formation in asset markets using the tatonnement pricing mechanism," mimeo.

Mankiw, N. Gregory and Stephen P. Zeldes, (1991), "The consumption of stockholders and nonstockholders," *Journal of Financial Economics*, 29, 97-112.

Noussair, Charles N. and Kenneth J. Matheny (2000), "An experimental study of decisions in dynamic optimization problems," *Economic Theory* 15, 389-419

Plott, Charles R. and Vernon L. Smith (2008), Eds., *Handbook of Experimental Economic Results* Vol.1, Amsterdam: North Holland.

Plott, Charles R. and S. Sunder (1982), "Efficiency of experimental security markets with insider trading," *Journal of Political Economy* 90, 663-698.

Porter, David P. and Vernon L. Smith (1995), "Futures contracting and dividend uncertainty in experimental asset markets," *Journal of Business* 68, 509-541.

Rabin, Matthew (2000), "Diminishing Marginal Utility of Wealth Cannot Explain Risk Aversion," in Choices, Values, and Frames, edited by Daniel Kahneman and Amos Tversky, New York: Cambridge University Press, 202-208.

Shiller, Robert J. (1981), Do stock prices move too much to be justified by subsequent changes in dividends?" *American Economic Review*, 71, 421—436.

Smith, Vernon L. (1962), "An experimental study of competitive market behavior," *Journal of Political Economy* 70, 111-137.

Smith, Vernon L., Gerry L. Suchanek, and Arlington W. Williams (1988), "Bubbles, crashes and endogenous expectations in experimental spot asset markets," *Econometrica* 56, 1119-51.

Stiglitz, Joseph E. (1970), "A consumption-oriented theory of the demand for financial assets and the term structure of interest rates," *Review of Economic Studies* 37, 321-351.

Wheatley, S. (1988), "Some tests of the consumption-based asset pricing model," *Journal of Monetary Economics* 22, 193—215.

Appendix - Regression Results

Table 1: Linear Regression of Mean HL Score on Median First Period Prices

```
. regress pinit hl hlevendifsq

     Source |       SS       df       MS                  Number of obs =      10
------------+------------------------------               F(  2,     7) =  119.35
      Model |  86.002833     2  43.0014165                Prob > F      =  0.0000
   Residual |  2.52216695    7  .360309565                R-squared     =  0.9715
------------+------------------------------               Adj R-squared =  0.9634
      Total |     88.525     9  9.83611111                Root MSE      =  .60026
------------------------------------------------------------------------------
      pinit |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
------------+-----------------------------------------------------------------
         hl |    3.60597   .3221715    11.19   0.000     2.844155    4.367784
hlevendifsq |   11.18167   1.446256     7.73   0.000     7.761817    14.60152
      _cons |  -4.786654   1.244665    -3.85   0.006     -7.72982   -1.843489
------------------------------------------------------------------------------
```

Table 2: R.E. Regression of HL Scores on Final Shareholdings in Linear Sessions

```
. xtreg avgsharefin2 hl if lin==1 ,i(session)

Random-effects GLS regression                   Number of obs      =        60
Group variable (i): session                     Number of groups   =         5
R-sq:  within  = 0.0000                         Obs per group: min =        12
       between = 0.0000                                        avg =      12.0
       overall = 0.0723                                        max =        12
Random effects u_i ~ Gaussian                   Wald chi2(1)       =      4.52
corr(u_i, X)       = 0 (assumed)                Prob > chi2        =    0.0335
------------------------------------------------------------------------------
avgsharefin2 |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
------------+-----------------------------------------------------------------
         hl |   .4579467   .2153831     2.13   0.033     .0358035    .8800899
      _cons |   .5613589   1.001782     0.56   0.575    -1.402099    2.524816
------------+-----------------------------------------------------------------
     sigma_u |          0
     sigma_e |  3.3157167
         rho |          0   (fraction of variance due to u_i)
------------------------------------------------------------------------------
```

Table 3: R.E. Regression of HL Scores on Final Shareholdings in Concave Sessions

```
. xtreg avgsharefin2 hl if lin==0 ,i(session)

Random-effects GLS regression                   Number of obs      =        60
Group variable (i): session                     Number of groups   =         5
R-sq:  within  = 0.0000                         Obs per group: min =        12
       between = 0.0000                                        avg =      12.0
       overall = 0.0117                                        max =        12
Random effects u_i ~ Gaussian                   Wald chi2(1)       =      0.69
corr(u_i, X)       = 0 (assumed)                Prob > chi2        =    0.4074
------------------------------------------------------------------------------
avgsharefin2 |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
------------+-----------------------------------------------------------------
         hl |  -.0969082   .1169705    -0.83   0.407    -.3261662    .1323499
      _cons |   2.847254   .4656838     6.11   0.000     1.934531    3.759978
------------+-----------------------------------------------------------------
     sigma_u |          0
     sigma_e |  1.6286249
         rho |          0   (fraction of variance due to u_i)
------------------------------------------------------------------------------
```

Table 4: R.E. Quadratic Regression of HL Scores on Net Expected Value Positions in Concave Sessions

```
. xtreg val hl hlsq if lin==0 ,i(session)

Random-effects GLS regression                 Number of obs      =        60
Group variable (i): session                   Number of groups   =         5
R-sq:  within  = 0.1093                       Obs per group: min =        12
       between = 0.1738                                      avg =      12.0
       overall = 0.1049                                      max =        12
Random effects u_i ~ Gaussian                 Wald chi2(2)       =      6.68
corr(u_i, X)       = 0 (assumed)              Prob > chi2        =    0.0355
------------------------------------------------------------------------------
         val |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          hl |    2.08459   .8316107     2.51   0.012     .4546632    3.714517
        hlsq |  -.1953346   .0891952    -2.19   0.029     -.370154   -.0205152
       _cons |  -4.373728   1.750486    -2.50   0.012    -7.804617   -.9428389
-------------+----------------------------------------------------------------
     sigma_u |          0
     sigma_e |  3.5726936
         rho |          0   (fraction of variance due to u_i)
------------------------------------------------------------------------------
```

Table 5: R.E. Quadratic Regression of HL Scores on Net Expected Value Positions in Linear Sessions

```
. xtreg val hl hlsq if lin==1 ,i(session)

Random-effects GLS regression                 Number of obs      =        60
Group variable (i): session                   Number of groups   =         5
R-sq:  within  = 0.0019                       Obs per group: min =        12
       between = 0.0004                                      avg =      12.0
       overall = 0.0017                                      max =        12
Random effects u_i ~ Gaussian                 Wald chi2(2)       =      0.10
corr(u_i, X)       = 0 (assumed)              Prob > chi2        =    0.9530
------------------------------------------------------------------------------
         val |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          hl |   .0301019   .7127489     0.04   0.966     -1.36686    1.427064
        hlsq |   .0032495   .0669103     0.05   0.961    -.1278922    .1343913
       _cons |  -.1977312   1.730851    -0.11   0.909    -3.590137    3.194675
-------------+----------------------------------------------------------------
     sigma_u |          0
     sigma_e |  3.1915954
         rho |          0   (fraction of variance due to u_i)
------------------------------------------------------------------------------
```

Table 6: F.E. Quadratic Regression of HL Scores on Period Earnings in Concave Sessions

```
. xtreg var2 var1 hlsq ,i(var5) fe

Fixed-effects (within) regression             Number of obs      =        60
Group variable (i): var5                      Number of groups   =         5
R-sq:  within  = 0.0732                       Obs per group: min =        12
       between = 0.0021                                      avg =      12.0
       overall = 0.0640                                      max =        12
                                              F(2,53)            =      2.09
corr(u_i, Xb)  = -0.0410                      Prob > F           =    0.1333
------------------------------------------------------------------------------
        var2 |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
        var1 |   .1523488   .0817133     1.86   0.068    -.0115474     .316245
        hlsq |   -.013366   .0088251    -1.51   0.136     -.031067     .004335
       _cons |   .3857246   .1708212     2.26   0.028     .0431006    .7283485
-------------+----------------------------------------------------------------
     sigma_u |  .10695612
     sigma_e |  .33065127
         rho |   .0947224   (fraction of variance due to u_i)
------------------------------------------------------------------------------
F test that all u_i=0:     F(4, 53) =     1.25             Prob > F = 0.3009
```