Margin Trading, Overpricing, and Synchronization Risk

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We provide experimental evidence that relaxing margin restrictions to allow more short selling can exacerbate overpricing, even though it reduces equilibrium price levels. This is because smart-money traders initially profit more by front-running optimistic investor sentiment than by disciplining prices. When short selling is not possible, competitive pressures among arbitrageurs rapidly drive prices to the equilibrium. However, the risk of margin calls slows the convergence process, because arbitrageurs who sell short too early face substantial losses if they are unable to synchronize their trades with other arbitrageurs (as in Abreu and Brunnermeier. 2002. *Journal of Financial Economics* 66(2–3):341–60; 2003. *Econometrica* 71(1):173–204). (*JEL* G14, C92)

Marginrequirements limit the access to capital that short sellers can use to exploit and eliminate overpricing. These requirements also impose the risk that unfavorable price movements will trigger a margin call that forces traders to close out positions at a loss before the overpricing is fully corrected (Shleifer and Vishny, 1997; Liu and Longstaff, 2004). Thus, relaxing margin requirements typically allows for more aggressive short selling, and reduces the equilibrium level of overpricing.[1] However, in this paper we predict (and show experimentally) that relaxing margin restrictions can also interfere with the ability of

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[1] Several papers have examined whether the run-up in prices of internet stocks and their collapse is attributable to short-selling constraints (e.g., Ofek and Richardson, 2003; Lamont and Thaler, 2003; D'Avolio, 2002; Geczy, Musto, and Reed, 2002; and Battalio and Schultz, 2006). Several theoretical and empirical papers have focused on the effect of short-sale constraints on stock prices including Miller (1977); Jones and Lamont (2002); Chen, Hong, and Stein (2002); Hong and Stein (2003); and Cohen et al. (2007). Studies have also examined options markets as proxies for short-selling constraints (e.g., Evans et al., forthcoming; and Ofek, Richardson, and Whitelaw, 2004).

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arbitrageurs to converge to equilibrium prices when arbitrageurs cannot predict other arbitrageurs' trading strategies. When this form of what Abreu and Brunnermeier (2002, 2003) call "synchronization risk" is severe, relaxing margin restrictions can actually exacerbate observed overpricing, even though it reduces equilibrium overpricing.

Toillustrate the effects of short-selling constraints on convergence to equilibrium, we model and implement a "smart-money" market that includes none of the risks that normally limit arbitrage in equilibrium. A group of smart-money traders knows fundamental value with certainty, so they do not face the fundamental risk that limits arbitrage in Figlewski (1979) and Shiller (1984). A nonstrategic "sentiment trader" buys shares steadily over the course of trading, representing an irrationally bullish group of traders similar to those in De Long et al. (1990). Unlike the irrational traders in De Long et al. (1990), however, our sentiment trader is perfectly predictable, so that smart-money traders do not face the noise trader risk that limits arbitrage in De Long et al. (1990) and Shleifer and Vishny (1997). The end point of trading is common knowledge, so that backward induction eliminates the possibility that the market is simply a "beauty contest" in which any price that traders expect can be a self-fulfilling prophecy (as in Keynes, 1964, p. 164). If the market were always in equilibrium (as assumed in most traditional models of trade) the commonly informed smart-money traders would always be able to predict one another's trading behavior, eliminating the synchronization risk that arises in the equilibrium models of Abreu and Brunnermeier (2002, 2003). Our analysis is motivated by the fact that synchronization risk will still arise as traders are attempting to learn the equilibrium (and hence learn to predict the behavior of the other traders). Until they do so, synchronization risk can hinder effective arbitrage, leading to overpricing.

We endow smart-money traders with finite capital, but also allow them to borrow money and shares at an interest rate of 0%, as long as they maintain an adequate ratio of equity to assets. If a trader's equity/assets ratio falls below a prespecified level, the trader is forced to close out his or her position until the ratio is sufficiently high. The market price is a linear function of demand, so in the absence of smart-money traders, the sentiment trader would drive prices upward during the course of trading. In equilibrium, when trading ends, the smart-money traders must have disciplined the sentiment trader to the extent possible given their access to capital. By backward induction, the price must equal the closing level at each moment of trade. Thus, the unique equilibrium price path is a horizontal line at or above fundamental value, with the equilibrium degree of overpricing declining as the smart-money traders' endowment increases, and as the required equity/assets ratio decreases (which increases the smart-money traders' access to capital).

We base our disequilibrium predictions on two observations. First, the smart-money game is a social dilemma like the prisoners' dilemma: smart-money traders collectively earn far greater profits by front-running the sentiment trader and delaying arbitrage of price errors than they earn in equilibrium. Based on the results of prior research on social dilemmas, we expect to see front-running and arbitrage in early trials of the smart-money game. Second, when margin restrictions are loose, traders must short sell aggressively to exploit deviations from equilibrium; this short selling exposes them to margin risk if they sell too long before others sell. These forms of risk, which do not exist in most social dilemmas, will slow or stop convergence to equilibrium in the smart-money game.

In our first experiment, we allow a robot to play the role of the sentiment trader, and nine humans to play the role of smart-money traders. We cross a manipulation of share endowment (high or low) with a manipulation of the equity/assets ratio (loose or tight). In early repetitions of each setting, traders buy heavily at the beginning of trade (effectively front-running the sentiment trader), and then delay arbitrage (so that prices form a clear “hump” shape), ultimately closing at a level at or slightly above that predicted by equilibrium. This pattern of front-running and delayed arbitrage yields very high profits for the smart-money traders, but also provides an opportunity for exploitation—a trader can earn extra profit by delaying arbitrage a little less than the others, and taking a larger portion of the arbitrage gains.

When traders either have large endowments or face tight-margin restrictions, competitive pressures drive prices to equilibrium in only a few repetitions. However, when traders have small endowments and loose-margin restrictions, prices continue to reflect the bubble-and-crash pattern that arises from front-running and delayed arbitrage. The bubbles persist because traders who arbitrage the front-running too much earlier than the other traders can incur a margin call, and because prices will continue to rise and increase the liability associated with their short position. Thus, convergence is delayed because margin risk arises during the learning process, even though it would not be present if traders were able to achieve the equilibrium.

We clarify our results in a second experiment in which the same traders return to participate in an additional set of markets. In this experiment, we endow traders with cash but no shares (so short selling is required in equilibrium), and manipulate the tightness of margin restrictions. While the markets with tight-margin restrictions require only a few repetitions to converge to an equilibrium with relatively high overpricing (because smart traders’ capital is limited), markets with loose margin show a persistent bubble-and-crash pattern created by front-running and delayed arbitrage. In fact, relaxing margin restrictions actually increases the peak market price, partly because traders have more money with which to engage in front-running, and partly because exploiting disequilibrium outcomes requires traders to rely more heavily on margin trading, and therefore face more margin risk.

Our results suggest that models of arbitrage are likely to have greater predictive power if they consider the factors that affect traders’ ability to learn equilibrium outcomes. One such factor is that disequilibrium outcomes (in particular, front-running and delayed arbitrage) result in far higher profits than the equilibrium outcome, and are therefore likely to be seen in early repetitions. Another factor is margin risk. We find little evidence that convergence to equilibrium is inhibited when traders have access to margin, but large enough endowments to avoid margin calls. One possibility is that margin risk increases the variability in returns to arbitrage (because it increases losses on the downside). Another possibility is that traders are more concerned by the possibility of out-of-pocket losses (which arise in our experiment only when margin calls are possible), than by opportunity costs of missing out on gains (which arise in all settings). This possibility is consistent with loss aversion, as characterized in prospect theory (Kahneman and Tversky, 1979), which is used effectively by Barberis, Huang, and Santos (2001) to explain a variety of other market anomalies. Future research might attempt to distinguish between overall risk profiles and loss aversion in arbitrage settings like the ones we examine here.

The next section describes our smart-money markets and characterizes the equilibrium outcome and the risks. Section 2 describes experiment 1 and its results. Section 3 describes experiment 2 and its results. Section 4 presents our conclusions, and discusses limitations and directions for future research.

1. Smart-Money Markets

In this section we construct and analyze a simple setting in which "smart-money" traders have the opportunity to exploit sentiment-driven investors. After describing the setting, we identify the unique equilibrium price path. We then establish the similarity of the game to a social dilemma by identifying front-running and delayed arbitrage as a disequilibrium outcome that Pareto dominates the equilibrium (from the perspective of the smart-money traders). Finally, we discuss how loose-margin restrictions are likely to hinder convergence to the equilibrium outcome by imposing margin risk upon those who attempt to exploit disequilibrium outcomes.

1.1 The smart-money market

We model smart-money markets by assuming that N smart-money traders (indexed from 1 to N) trade a security for T periods, along with a nonstrategic sentiment trader (indexed as trader 0). All smart-money traders know that the security pays a liquidating dividend V at the end of trade; thus, the market includes no fundamental risk (Figlewski, 1979; Shiller, 1984). The sentiment trader buys N shares in each period t from 1 to T. This trader captures investor sentiment in a manner similar to the noise trader of De Long et al. (1990). However, our sentiment trader is perfectly predictable, eliminating the possibility that "noise trader risk" would interfere with arbitrageurs' ability to discipline prices. For simplicity, we hereafter refer to smart-money traders simply as "traders."

In period 0, traders hold identical endowments of $C(0) \geq 0$ in cash, $Q(0) \geq 0$ in shares, and $D(0) = 0$ in debt. In each period, each trader i buys or sells some real number of shares $s_i(t)$. Traders can borrow money to buy shares, or borrow shares to sell short, as long as doing so does not violate a minimum equity ratio (R) requirement that equity/assets $> R^*$ (i.e., $R > R^*$). Assets are defined as cash plus the current market value of any shares owned. Liabilities are defined as debt plus the current market value of any shares sold short. Equity is the excess of assets over liabilities. Traders purchase shares with cash before resorting to borrowing, and sell shares they own before resorting to short selling. We make no explicit assumptions about the sentiment trader's endowments or access to capital, other than assuming the sentiment trader is able to buy N shares in every period.

We assume that trade is mediated by a market maker or specialist who fills all trades at a price P that is a linear function of cumulative net demand. Specifically,

$$P(t) = V + k \sum_{i=0}^{N} \sum_{j=0}^{t} s_i(j), \tag{1}$$

where V is the liquidating dividend paid on the security at the end of trade, $k > 0$, and $s_i(j)$ is the trade by trader i in period j. This assumption is similar to that imposed by Hong and Stein (1999), as well as by traditional microstructure models like Kyle (1985), and allows us to focus entirely on the behavior of the smart-money traders, who are our target of interest. Imposing a linear demand function may allow specialists to earn nonzero profits (because they are not engaged in rational competition with other traders who have the power to set prices and fill trades). The assumption that the specialist fills all trades based on the linear demand function also requires that the specialist have unlimited cash and shares to fill any imbalance. We discuss the implications of relaxing this assumption in the conclusion of the paper.

In each period, net demand is subdivided into infinitesimal parts and executed in a random order, with a linear price adjustment after each trade. There are no transaction costs or bid-ask spread. Without loss of generality we assume that $k = 1/N$, so that price rises by \$1 if each trader buys one share.

1.2 Equilibrium

We define the symmetric competitive equilibrium as the market outcome that satisfies the following requirements:

1.2.1 No-arbitrage requirement Given the opportunity to trade an additional share after observing past and current market prices, no trader would expect positive profit from doing so in any period.

1.2.2 Symmetry requirement All traders take the same trading actions in each period.

We identify the unique equilibrium price path through three observations based on backward induction. First, we observe that the equilibrium price at time T must be equal to V if traders still have the ability to sell additional shares.

Otherwise, a trader could trade a share for certain profit. The price can close above V only if traders have hit their minimum equity ratio ($R(T) = R^*$) and can sell no more shares. We use the variable $d^* = P(T) - V$ to denote the deviation of the closing equilibrium price from value.

Next, we observe that any price difference between $P(T)$ and $P(T-1)$ would allow a profitable trade (opening a position in the first period and closing it in the next), as long as traders have the capital to trade in the profitable direction. Therefore, the no-arbitrage requirement implies that $P(T-1) = P(T)$, unless margin restrictions prevent one of the trades. By backward induction, it is clear that this statement is also true for any other consecutive pair of periods, so $P(t) = P(t-1)$, for all t satisfying $0 < t < T$, as long as traders are able to both buy and sell.

Finally, we observe that the margin ratio cannot be binding before period T, unless traders begin with an insufficient equity to trade in any period. To see why, assume that $d^* > 0$, which implies that traders cannot sell additional shares in period T. Prices rise in every period in which that constraint is binding, so traders naturally delay any sales as long as possible. Thus, assuming traders are unable to sell any shares in period T leads to a contradiction, unless they were never able to sell shares. Because the margin ratio is not binding until period T, prices must remain steady at $V + d^*$ for some number of periods before period T.

The exact price path depends on the traders' initial endowments of cash and shares. In Appendix A, we construct equilibria for different endowments. We also show that if traders can buy enough shares in period 1 to drive prices up to $V + d^*$ in period 0, the price path is simply a horizontal line at $P(T)$, with traders selling exactly enough shares in each subsequent period to keep the sentiment trader from driving prices upward. As in most models of arbitrage, it is impossible to predict future price changes (in fact, there aren't any), and the equilibrium price is as close to value as the arbitrageurs' capital will allow. However, limited initial endowments and high minimum equity ratios can allow the equilibrium price to be above fundamental value because the smart-money traders cannot fully discipline the sentiment trader. Note that under the definition used in King et al. (1993); Lei, Noussair, and Plott (2001); and Noussair, Robin, and Ruffieux (2001), this equilibrium price represents a bubble, because there is "trade at high volume at prices considerably at variance from fundamental values."

1.3 Front-running and delayed arbitrage is a Pareto-superior disequilibrium outcome

Smart-money traders collectively extract the most money from the sentiment trader by buying as many shares as possible (beyond those necessary to drive prices up to $V + d^*$) before the sentiment trader begins buying, and waiting until period T to sell those shares (after the sentiment trader has driven price up as much as possible). To see why, note that after driving prices to $V + d^*$, an additional share purchased in period 0 (before the sentiment trader buys) is purchased at the average of $V + d^*$ and $V + d^* + F(0)$, where $F(0)$ is the number of shares purchased by each trader in period 0 as they front-run investor sentiment. Assuming that all traders follow the strategy of front-running and maximally delayed arbitrage, the additional share is sold in period T at the average of $V + d^*$ (the price in period T) and $V + d^* + F(0) + T$. Because this average is always greater than the average purchase price in period 0, buying an additional share in period 0 and reselling that share in period T is always profitable.

The fact that a disequilibrium outcome Pareto dominates the equilibrium outcome makes the smart-money game a form of a social dilemma, like the prisoners' dilemma (Tucker, 1950) or the gift exchange (Akerlof, 1982). The smart-money game is particularly closely tied to the centipede game (Mckelvey and Palfrey, 1992; Rosenthal, 1981), in which a pot of money is placed on a table between two players. The players alternate for a known, finite and even number of turns, each deciding whether to end the game or not. A player who ends the game receives 2/3 of the pot and the other player receives the remainder. If they choose not to end the game, the pot increases by 50% and the other player is given the opportunity to end the game. If no one ever chooses to end the game prematurely, player 2 gets 2/3 of the pot. If the game has a sufficient number of rounds, both players are better off by deciding to continue the game until the final round than they are if the first player ends the game immediately. However, the latter outcome is the unique subgame-perfect equilibrium. The proof is by backward induction. Because the second player gets 2/3 of the pot if no one chooses to end the game, the first player prefers to do so in the second-to-last round, in order to receive 2/3 of the current pot, which is greater than 1/3 of the (50% larger) pot in the next round (1/3 * 150% = 1/2). By identical reasoning, the second player will end the game in the immediately preceding period, and so on.

1.4 Exploiting disequilibrium exposes traders to margin risk

Choosing to continue play in the centipede game is similar to choosing to delay arbitrage by one period in our smart-money game: in both cases, a player allows the total pot of available gains to increase, but faces the risk that other players will take the majority of those gains. The settings are also similar in that the best reply to a disequilibrium strategy of delayed gains taking is to take gains in the round immediately preceding gains taking of the other player. In both cases, exploiting a disequilibrium strategy imposes the "synchronization risk" (Abreu and Brunnermeier, 2002, 2003) that the player will fail to time gains taking optimally, given the (unknown) strategies of the other players.

When margin trading is impossible, the similarity of the smart-money and centipede games suggests that the smart-money game will generate results similar to those of centipede games. In centipede games, players initially choose to delay gains taking until the end of the game, but the ending time creeps forward as players learn by experience that they can earn higher payoffs by taking gains earlier (Mckelvey and Palfrey, 1992). Similarly, we expect players to engage in front-running and delayed arbitrage in early rounds, but that arbitrage is less delayed as players learn by experience that they can earn higher payoffs by delaying arbitrage a little less (and, ultimately, front-running less).

However, when margin trading is possible, choosing to accelerate arbitrage may require taking a short position, which in turn imposes the risk of out-of-pocket losses if prices continue to rise long enough to trigger a margin call that forces the short seller to buy shares back at a higher price. This "margin risk" (Liu and Longstaff, 2004) is likely to slow players' convergence to equilibrium.

Our assumption that traders begin in disequilibrium does not require a particularly sharp deviation from the usual assumptions underlying economic modeling. Even if all players are perfectly rational, slight deviations from common knowledge of that rationality can lead to predictions of front-running and delayed arbitrage, just as they can lead to extended cooperation in a repeated prisoners' dilemma or centipede game (Kreps et al., 1982). From this perspective, each play of the smart-money game is like a repeated social dilemma, but successive iterations allow players to approach common knowledge more closely.

We do not attempt to characterize the precise conditions under which margin risk is likely to hinder convergence most severely. However, we do offer the following observations. First, margin risk cannot exist unless traders are permitted to trade on margin (i.e., the minimum equity ratio is less than 1). Loosening margin requirements (assuming they are already less than 1) has offsetting influences—it allows traders to hold short positions longer, and also lowers the equilibrium price because arbitrageurs have more access to capital with which to discipline overpricing, thus reducing equilibrium front-running. However, with less equilibrium front-running, arbitrageurs must use more margin trading to discipline prices (rather than using shares purchased during front-running), making them more susceptible to margin risk. Endowing traders with fewer shares also increases the margin trading necessary to discipline prices. Thus, we expect convergence to be most difficult when margin requirements are loose and low share endowments require extensive short selling in equilibrium. We test this conjecture by manipulating margin requirements and share endowments in a laboratory setting that captures the salient features of smart-money markets.

2. Experiment 1

Our goal in this experiment is to examine price behavior in smart-money games under conditions of high and low margin risk. Four cohorts of nine traders participated in 90-minute trading sessions that involved trading 24 securities each. Each security paid a liquidating dividend of $500 at the end of 90 seconds of trading (similar to trading sessions in Bloomfield, Taylor, and Zhou, 2008). (Unless otherwise indicated, all prices and winnings are denominated in laboratory dollars ($), an artificial currency that is converted into US currency at the end of the experiment.) A robot purchased nine shares every second for 80 seconds, starting 5 seconds into trading and ending 5 seconds before the end of the market. Market prices approximate the linear function described in the model, modified so that all prices are integers. Specifically, Market Price = 500 + INT[(Cumulative Imbalance)/9], where the cumulative imbalance is defined as the total number of shares bought since the beginning of trade minus the number of shares sold, including trades from the robot.[2]

We imposed a transaction cost of $1; thus, traders who wished to buy (sell) at a given price paid $1 more (received $1 less) than that price. This transaction cost ensures that trades reflect traders' sincere belief that they can predict future price changes, but has little effect on predicted behavior.

2.1 Treatments

Each cohort traded six securities in each of four experimental settings that were created by crossing initial share endowments (90 or 10 shares) with margin trading requirements (tight or loose). We used a Latin-squares design to balance the order in which cohorts trade in each of the experimental settings, so there is no concern that differences across treatments are driven by differences in experience. We use 90T (90L) to refer to the setting with a 90-share endowment and tight- (loose-) margin limits, and 10T (10L) to refer to the setting with a 10-share endowment and tight- (loose-) margin limits.

Traders with a tight-margin requirement had to maintain a minimum equity ratio (the ratio of equity to assets) of 1.0, which precludes any borrowing or short selling. Traders with a loose-margin requirement had to maintain a minimum equity ratio of 0.6. Since the equity ratio is a function of market price, a movement in price could potentially cause a trader to drop below the minimum equity ratio requirement. If that happened, traders were forced to close out their trading positions until their equity ratio was 0.8. Traders were endowed with $45,000 cash.

The equilibrium price is 570 when traders are endowed with 10 shares and face tight-margin requirements, 504 when traders are endowed with 10 shares and face loose-margin requirements, and 500 when traders are endowed with 90 shares (regardless of margin requirements).[3] Margin risk is absent in 90T and 10T, when tight-margin requirements prohibit short selling. Margin risk is slight in 90L, when traders have high share endowments and access to margin—traders have so much capital that they can exploit deviations from equilibrium quite aggressively without risking a margin call. Margin risk is severe in 10L, when traders have loose-margin requirements, but few shares. In this setting, the low equilibrium price implies that a trader wishing to exploit

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[2] The INT operator truncates fractions; thus, if sentiment and smart-money traders had cumulatively bought 80 shares and sold 50, INT[(80−50)/9] = 3, the market price would rise to 503 regardless of the order of trade; a purchase of another six shares would increase price to 504.

[3] See Appendix A for equilibrium calculations.

deviations from equilibrium would be able to sell only 14 shares before taking on a short position (the 10 endowed shares plus the 4 bought during equilibrium front-running). Thus, we expect to see only weak convergence to equilibrium in 10L.

2.2 Administration of experiment

The experiment was conducted in the Business Simulation Laboratory at the Johnson Graduate School of Management at Cornell University. The participants in the experiment were graduate and undergraduate students from a variety of programs at Cornell, primarily the Johnson School's MBA program and Cornell University's engineering and physics programs.

Upon arriving at the laboratory, each subject received detailed written instructions, a copy of which is given in Appendices B (for experiment 1) and C (for experiment 2). The instructions were reviewed in detail by the experiment administrator, who also answered any questions. The administrator then guided participants through the use and interpretation of the computer interface by trading four practice securities, which did not affect participants' cash winnings.

Regarding conversion of laboratory dollars to USD, participants were not given the exact exchange rate, but were told that, for nonpractice rounds, gains in laboratory dollars would increase their cash payoff, losses would decrease their cash payoff, and that the gains and losses of other people in their market would have no effect on their payment. By not telling participants an exact exchange rate, we mitigate the likelihood that we would signal to traders the profits we expect them to make. Consistent with Cornell University's guidelines for human subject recruitment, our solicitation indicated the average USD payments participants could expect. If we had also provided the equation translating trading gains into USD payments, participants could infer the extent of front-running and delayed arbitrage we were anticipating. Our method avoids this possible demand effect. Our payment instructions still achieve salience (Smith, 1982), because participants are well aware that increasing their trading gains would increase their cash payments. Our payment method does make it difficult for participants to assess the exact worth of those gains; however, our predictions are not sensitive to the degree of participants' risk aversion. Moreover, we believe that any effects of our payment scheme are minimal (other than allowing us to eliminate demand effects), in part because Bloomfield, O'Hara, and Saar (forthcoming, 2007) show that a payment scheme similar to the one used here generated trading behavior almost indistinguishable from that generated by a more traditional payment scheme.

The trading screen continuously reported to traders their current cash balance, share exposure, average cost or revenue per share in inventory, realized and unrealized gains, and their current equity ratio. The screen also reported the current market price and the number of shares bought and sold by them and by the market. Finally, a graph on the lower right of the screen depicted price and volume over time. Traders could adjust this chart to track market activity in increments of 1, 2, 5, 10, and 20 seconds.

2.3 Results

Average price paths for the 96 markets in experiment 1 are shown in Figure 1. Each graph shows the average price across cohorts for the six within-cohort repetitions in each treatment of the 2×2 design, as well as the equilibrium price in each setting. Casual inspection shows striking patterns. With high share endowments and loose-margin requirements, all markets quickly converge to the equilibrium in which the price remains at 500 throughout trading. With high share endowments and tight-margin requirements, markets fall only slightly short of convergence to the equilibrium. With low share endowments and tight-margin ratios, markets quickly converge to the equilibrium in which they front-run prices up to 570 and then sell shares at a steady rate to keep prices at that level. In contrast, the price paths deviate markedly from equilibrium when low share endowments and loose-margin ratios combine to create margin risk. Consistent with our predictions, all markets in this setting show consistent overpricing, with prices rising sharply early in trading, and falling back toward fundamental value later on. However, contrary to our expectations, prices close well above equilibrium levels. We discuss possible reasons for this below and address these possibilities in experiment 2.

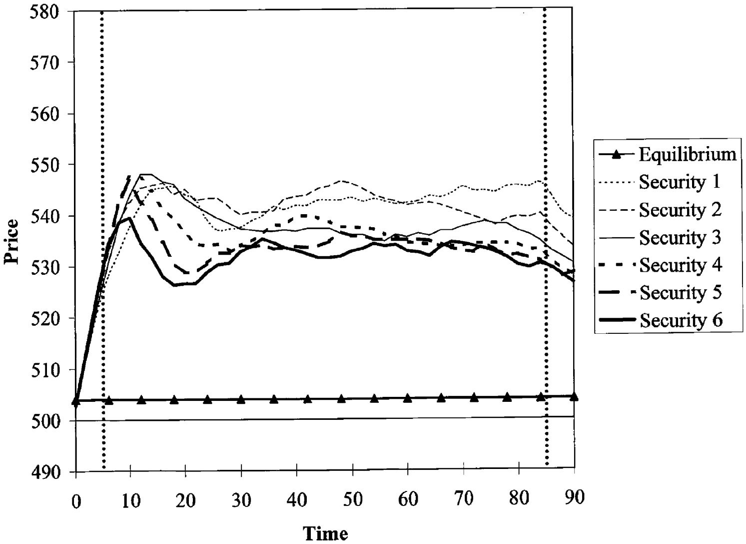
2.3.1 Deviations from equilibrium price paths For a more detailed analysis of deviation from equilibrium, we approximate for each price path the time-averaged absolute deviation of market price from the equilibrium price path. Note that our theory does not predict only the closing market price; rather, it predicts the entire price path, from the opening of the market to the close. Our theory predicts that observed closing prices will approximate equilibrium closing prices in all four settings. However, we predict that early price behavior (front-running when the market opens and delayed arbitrage in the middle of trade) will vary across treatments. Thus, we must analyze the deviation of the observed price path from the actual price path throughout the course of trade.

Because our laboratory network was able to process only about 60 trades per second, we adjust the equilibrium price path in the low-endowment/tight-margin setting to rise from 500 to 570 gradually over the first 10 seconds of trading. We approximate the area between the actual and equilibrium price paths using the trapezoidal rule, with the area equal to

$$\sum_{i=1}^{n} \frac{1}{2} \times h \times [f((a+(i-1)h) + f(a+ih)], \tag{2}$$

where $h = 0.1$ seconds, f is the absolute difference between the actual and equilibrium price at any given time, $a = 0$, and $n = 900$ (90 seconds in the

A



B

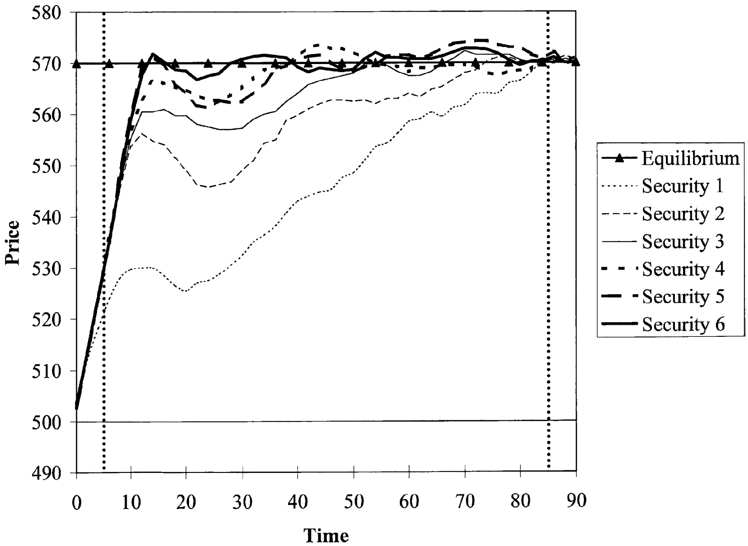


Figure 1
Price paths for experiment 1
In experiment 1, each cohort traded six securities in each of our four experimental settings that were created by crossing initial share endowment (90 or 10) with margin requirement (loose (*L*) or tight (*T*)). Price paths are shown grouped by treatment and averaged across cohorts, with time on the horizontal axis and price on the vertical axis. Dotted vertical lines at 5 and 85 seconds mark the beginning and end of robot buying during the 90-second trading periods. A horizontal line labeled "Equilibrium" in the key indicates the equilibrium price in each setting. The other security numbers in the key indicate the order in which securities were traded. Panel A: Treatment 10L (10-share endowment, loose-margin limits). Panel B: Treatment 10T (10-share endowment, tight-margin limits). Panel C: Treatment 90L (90-share endowment, loose-margin limits). Panel D: Treatment 90T (90-share endowment, tight-margin limits).

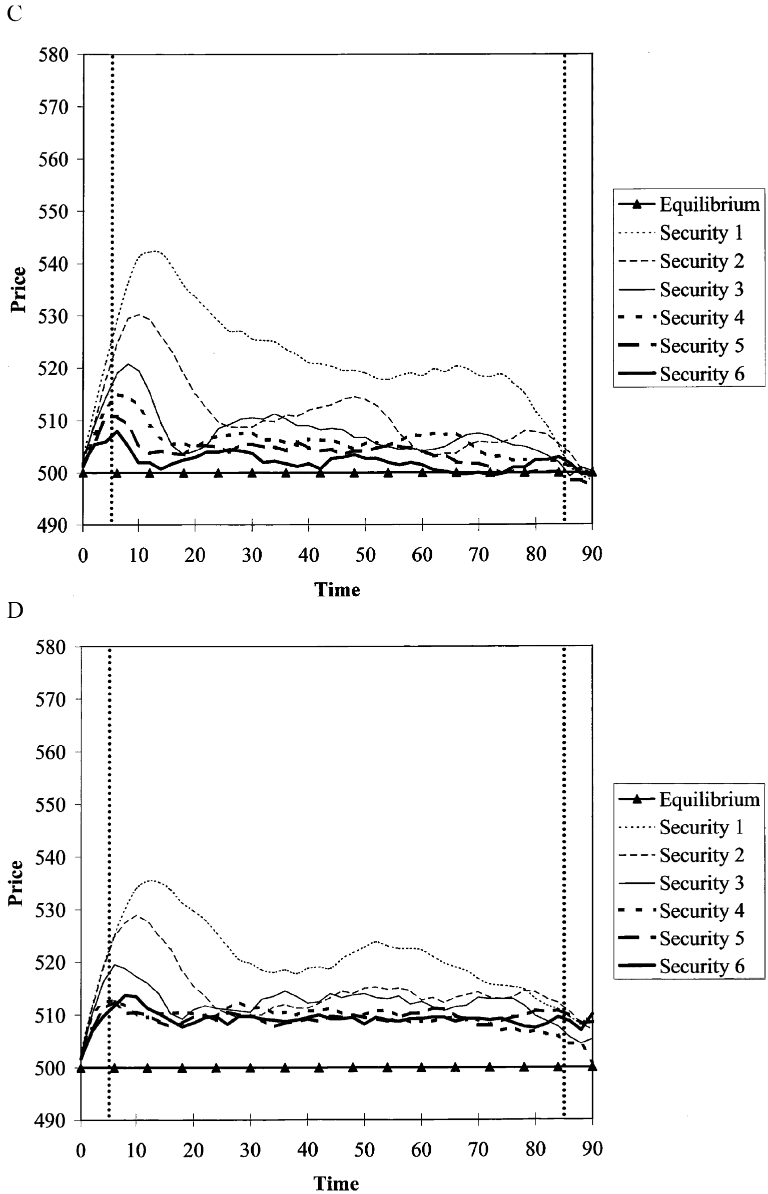


Figure 1
(Continued)

Table 1
Deviation from equilibrium in experiment 1

	1	2	3	4	5	6	Average
		Panel A					
90T	21.08	15.09	12.54	9.75	9.90	9.70	13.01
90L	22.18	11.73	8.04	6.65	4.26	2.71	9.26
10T	−20.95	−9.18	−4.68	−2.29	−1.36	−0.52	−6.49
10L	36.58	36.55	32.82	31.44	29.27	27.47	32.36
Average	14.72	13.56	12.58	11.38	10.52	9.93	

Source	Type III SS	Mean square	*F*-value	*p*-value
	Panel B			
Shares	77.40	77.40	0.19	0.60
Margin	7395.22	7395.22	39.39	0.01
Rep	274.43	54.88	2.65	0.06
Shares * margin	10892.32	10892.32	33.61	0.01
Shares * rep	1305.26	261.05	11.27	0.00
Margin * rep	930.00	186.00	37.76	0.00
Shares * margin * rep	363.89	72.77	1.58	0.22

Panel A of this table provides information on primary dependent variable defined as the average deviation of the actual price path from the equilibrium price path per second. We calculate the area between the actual and equilibrium price path using the trapezoidal rule. Therefore the area between the two price paths is given by

$$\sum_{i=1}^{n} \frac{1}{2} \times h \times [f((a + (i-1)h) + f(a + ih)],$$

where h is 0.1 seconds and f is the difference between the actual and equilibrium price at any given time, $a = 0$ and $n =$ number of seconds in trading period/0.1. Columns 1–6 are the replications with 1 being the earliest replication and 6 being the latest. 90T refers to the setting with a share endowment of 90 and tight-margin limits (the minimum equity ratio is 1.0, so no margin trading is allowed). 90L reflects a share endowment of 90 shares and loose-margin limits (the minimum equity ratio is 0.6, so traders may trade on margin as long as their equity-to-assets ratio is no less than 0.6). Treatment 10T has a share endowment of 10 and tight-margin limits, and treatment 10L has a share endowment of 10 and loose-margin limits. Average reflects the average of the various columns/rows. Panel B provides results of the repeated measures ANOVA. Shares is 1 if the share endowment is 90 and 0 if the share endowment is 10. Margin is 1 in the loose-margin setting (0.6) and 0 in the tight-margin setting (1.0). Rep is the replication number and takes a value of 1 through 6.

trading period divided by 0.1). We then divide this area by 90 to get the per-second deviation from equilibrium.

Table 1, panel A, reports the per-second signed difference between the average price paths and the equilibrium price for each replication in each treatment. Averaged over all six replications, we see an average per-second deviation of 32.36 in 10L, when low share endowments and access to margin combine to create severe disequilibrium margin risk. In contrast, the average per-second deviation is only 13.01 in 90T, 9.26 in 90L, and −6.49 in 10T. Consistent with the Pareto dominance of the collectively optimal outcome of front-running and delayed arbitrage, prices are too high in every setting but the one that already involves substantial front-running in equilibrium.

To assess the statistical significance of these effects, we conduct a repeated-measures ANOVA with factors for cohort (1–4), share endowment (high, low), margin requirement (tight, loose), and repetition (1–6). Our repeated-measures analysis accounts for any lack of independence between multiple observations from members of the same cohort.[4] Intuitively, a treatment has a statistically significant effect only if the effect of the treatment within each cohort is large relative to the variation in the effect across cohorts. As shown in panel B of Table 1, we find a statistically significant interaction between margin requirement and share endowment ($p = 0.01$), which confirms that the low-endowment/loose-margin setting (where margin risk is the highest) is further from equilibrium than the other three settings.

The repeated-measures analysis also finds a repetition effect, confirming that the markets are drawing closer to equilibrium as traders gain experience ($p = 0.06$). However, margin risk appears to hinder convergence substantially. From the first to the sixth repetition, the deviation from equilibrium drops by about 25% in 10L; in contrast, the deviation from equilibrium drops by 54%, 88%, and 99% in 90L, 90T, and 10T, respectively. Movement toward equilibrium is not statistically significant in 10L ($p = 0.396$), but is strongly significant in 10T ($p = 0.006$), and marginally significant in 90L ($p = 0.051$) and 90T ($p = 0.111$). Using a contrast, we also find that the deviation from equilibrium in the first repetition is only marginally larger in 10L than in the other settings ($p = 0.111$), but is substantially larger in the last repetition ($p < 0.001$). Thus, we conclude that disequilibrium margin risk hinders traders' ability to converge toward equilibrium.

2.3.2 Profits To further examine deviations from equilibrium trading in our markets, we report in Table 2, panel A, the profit per trader-second in excess of the equilibrium profit in each of the four experimental settings.[5] Equilibrium profits are zero in both high share endowment settings (90T and 90L), in which prices should never deviate from fundamental value. Equilibrium profits are positive in the low share endowment settings because traders sell 80 shares at prices above fundamental value, some of which they were endowed with and some of which they would have purchased at average prices midway between the equilibrium price and fundamental value while participating in equilibrium front-running.[6]

The results from traders' profits are consistent with our analysis of price paths. In the setting where disequilibrium margin risk is high, realized profits trend very little toward equilibrium profits as traders gain experience with each repetition. Profits in 10L are \$23.30 above equilibrium in the first repetition, and drop to \$19.78 in the last repetition, representing only a 15% move toward equilibrium. In contrast, in settings where the disequilibrium margin risk is low,

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[4] See Libby, Bloomfield, Nelson (2002) for a detailed discussion of the nature and uses of repeated-measures designs.

[5] We divide by traders as well as seconds to allow ready comparison to the average price deviations in Table 1.

[6] Specifically, the equilibrium requires each trader in 10T to buy 70 shares at an average price of \$535 when they front run, and then sell 80 shares at an average price of \$570, yielding a gain of \$35/second per trader over the 90 seconds of trade. The equilibrium requires traders in 10L to buy four shares at an average price of \$502 and sell 80 shares at an average price of \$504, yielding a trading gain of about \$3.50/second per trader.

Table 2
Winnings in experiment 1

	1	2	3	4	5	6	Average
			Panel A				
90T	17.00	11.71	10.02	7.54	6.69	7.05	10.00
90L	19.48	9.41	5.98	4.90	2.69	1.28	7.29
10T	−22.64	−11.29	−6.70	−4.43	−3.96	−2.78	−8.63
10L	23.30	26.00	23.96	23.27	21.10	19.78	22.90
Average	9.28	8.96	8.31	7.82	6.63	6.33	

Source	Type III SS	Mean square	F-value	p-value
		Panel B		
Shares	54.92	54.92	0.20	0.68
Margin	4985.14	4985.14	60.50	0.00
Rep	116.40	23.28	1.31	0.31
Shares * margin	7035.84	7035.84	34.45	0.01
Shares * rep	144.75	289.39	15.09	0.00
Margin * rep	646.35	129.27	25.83	0.00
Shares * margin * rep	190.76	38.15	0.98	0.46

Winnings refer to the difference between the liquidating value of a trader's position (including cash) and the initial endowment of cash and shares. Panel A provides information on the average winnings per trader per second across the various treatments and repetitions. Panel B provides results of the repeated measures ANOVA with the average winnings per trader per second in each trading round as the dependent variable. 90T refers to the setting with a share endowment of 90 and tight-margin limits (the minimum equity ratio is 1.0, so no margin trading is allowed). 90L reflects a share endowment of 90 and loose-margin limits (the minimum equity ratio is 0.6, so traders may trade on margin as long as their equity-to-assets ratio is no less than 0.6). Treatment 10T has a share endowment of 10 and tight-margin limits; treatment 10L has a share endowment of 10 and loose-margin limits. Shares is 1 if the share endowment is 90 and 0 if the share endowment is 10. Margin is 1 in the loose-margin setting (0.6) and 0 in the tight-margin setting (1.0). Rep is the replication number and takes a value of 1 through 6.

realized profits display a sharper trend toward equilibrium profits with each repetition. Excess profits are \$17.00 and \$19.48 in the first repetition and \$7.05 and \$1.28 in the last repetition of 90T and 90L settings, respectively, which represent a 59% and 93% drop in profits toward the equilibrium profit level of zero. Similarly, profits in 10T are \$22.64 below equilibrium profits in the first repetition (because traders are not front-running enough) and move up to \$2.78 below equilibrium in the last repetition, representing an 88% shift toward the equilibrium level of \$35. Statistical analyses of movement toward equilibrium levels of profits show patterns similar to those shown in our analysis of deviation from equilibrium prices. Using a contrast, we find that the absolute deviation from equilibrium in the first repetition is only marginally larger in 10L than in the other settings ($p = 0.19$), but is substantially larger in the last repetition ($p < 0.01$). Thus, we conclude that disequilibrium margin risk hinders traders' ability to converge toward equilibrium.

Recall that all human and robot trades were filled by a robot specialist. Additional analyses (untabulated) show that the specialist averages profits of \$0.95 in 90L, 1.31 in 90T, \$2.97 in 10L, and \$11.79 in 10T. Specialists in our markets earn profits in two ways: by taking on trading positions at favorable prices when supply and demand are unequal and by capturing the bid-ask spread when supply and demand are equal (but nonzero). The small but positive profits in the 90L, 90T, and 10L settings reflect the gains from capturing the bid-ask spread. (The specialist does not take a substantial position over the course of trading, because net cumulative supply is close to zero). The large profits in the 10T setting are driven by the fact that the specialist takes on a large short position at prices above fundamental value as traders engage in front-running, and holds that position until trade closes (while also capturing the bid-ask spread on subsequent trades).

While we predicted (and found) that deviations from equilibrium would be greatest in the cell with low share endowments and loose-margin requirements, one aspect of that deviation is quite different from our prediction: closing prices are also substantially above the equilibrium level. This deviation from our expectation that closing price would be close to the equilibrium price appears to be driven by traders' reluctance to exploit loose-margin requirements. When traders are permitted an equity ratio as low as 0.60, only one-fourth of traders end trading with a equity ratio of 0.61 or lower, while only half end with an equity ratio less than 0.67. Fully one-fourth of our traders end trading with an equity ratio of 1, indicating that they did not sell any shares short, despite the ability to do so in the final seconds of trade with negligible risk. One possibility is that some traders did not fully understand their trading options in this market, and thus deviations from equilibrium reflect the amount of capital participants are willing to use.[7] We address this issue, along with others, in our second experiment.

3. Experiment 2

3.1 Motivation and design

We attribute the overpricing in experiment 1 to traders' reluctance to risk losses as they exploit deviations from equilibrium. However, it is possible that our results are driven by the relative inexperience of our traders. Moreover, prices may be consistent with an "empirical" equilibrium that reflects the amount of capital they are actually willing to use. We clarify the importance of margin risk by conducting a second experiment. As in experiment 1, we manipulate margin requirements to alter disequilibrium margin risk. To determine whether the results of experiment 1 were driven by trader inexperience, we used the same traders in experiment 2. We also adjust the parameters to strengthen our treatment effect, while ensuring that the equilibrium price will be low even if traders use only part of their capital. Specifically, traders begin with \$15,000 and zero shares, and face minimum equity ratios of either 0.66 (tight) or 0.33

[7] If traders take as given that only a portion of possible capital will be deployed in the market, the equilibrium price path will be a horizontal line at a price higher than we have calculated. However, we find that average prices are higher than closing prices even in the final repetition of this setting in all four cohorts, indicating that traders still attempt to front run and delay arbitrage, even if the target equilibrium price is taken to be the actual closing price (rather than the equilibrium price we calculated assuming that all traders would exploit all of their access to capital).

(loose) (for consistency with experiment 1, we use 0T (0L) to refer to the setting with a zero-share endowment and tight- (loose-) margin limits). In the event of these limits being crossed, the computer automatically sells enough of the shares owned, or buys back enough of the shares sold short, to bring the equity ratio to 0.833 or 0.667, respectively. The robot trades for 50 seconds, starting 10 seconds after trading begins and ending 20 seconds before trading ends.

As calculated in Appendix A, the equilibrium prices are 500 with a loose-margin requirement and 535 with a tight-margin requirement. While both settings require short selling, disequilibrium margin risk is much more severe with loose-margin requirements, because the lack of equilibrium front-running forces traders to begin short selling sooner if they are to exploit deviations from equilibrium. The loose-margin ratio is sufficiently loose that the equilibrium price would remain at 500 even if traders' collective equity ratio never dropped below 37.5. Further, the additional 15 seconds of trade after the end of robot trading, along with the participants' greater experience, should increase the effective use of capital. As a result, overpricing exacerbated by margin risk should be clearly distinguishable from overpricing created by an unwillingness to trade on margin.

Overall, the design of experiment 2 is a 1×2 factorial design that manipulates margin requirements (tight, loose).[8] As in experiment 1, cohorts experienced the treatments in different (balanced) orders to control for the effects of experience. The procedure and incentives are similar to those in experiment 1. Because all traders in experiment 2 had previously gained experience by participating in experiment 1, the administrator guided participants through the use and interpretation of the computer interface by trading only one practice security (which did not affect participants' cash winnings).

3.2 Results

Average price paths from the 48 markets in experiment 2 are shown in panels A and B of Figure 2. Each graph shows the average price across cohorts for the six repetitions in each treatment of the design, as well as the equilibrium price in each setting. Visual inspection confirms our predictions. Price paths are quite close to equilibrium when tight-margin requirements reduce margin risk. Despite the fact that loosening margin requirements makes equilibrium prices lower, it also increases margin risk leading to greater and more persistent overpricing. Cohorts with loose-margin requirements show continued overpricing toward the beginning of trade (with excessive front-running and delayed arbitrage) even after multiple repetitions. Further, prices are much closer to equilibrium at the close of trading than those in experiment 1, likely the

[8] During the experimental sessions, participants in experiment two also traded in separate markets investigating other possible factors affecting mispricing. These markets are not part of the current study, so are not discussed further. Our design balances the order of all treatments, so we do not expect the unreported treatments to influence statistical tests of behavior in the reported treatments.

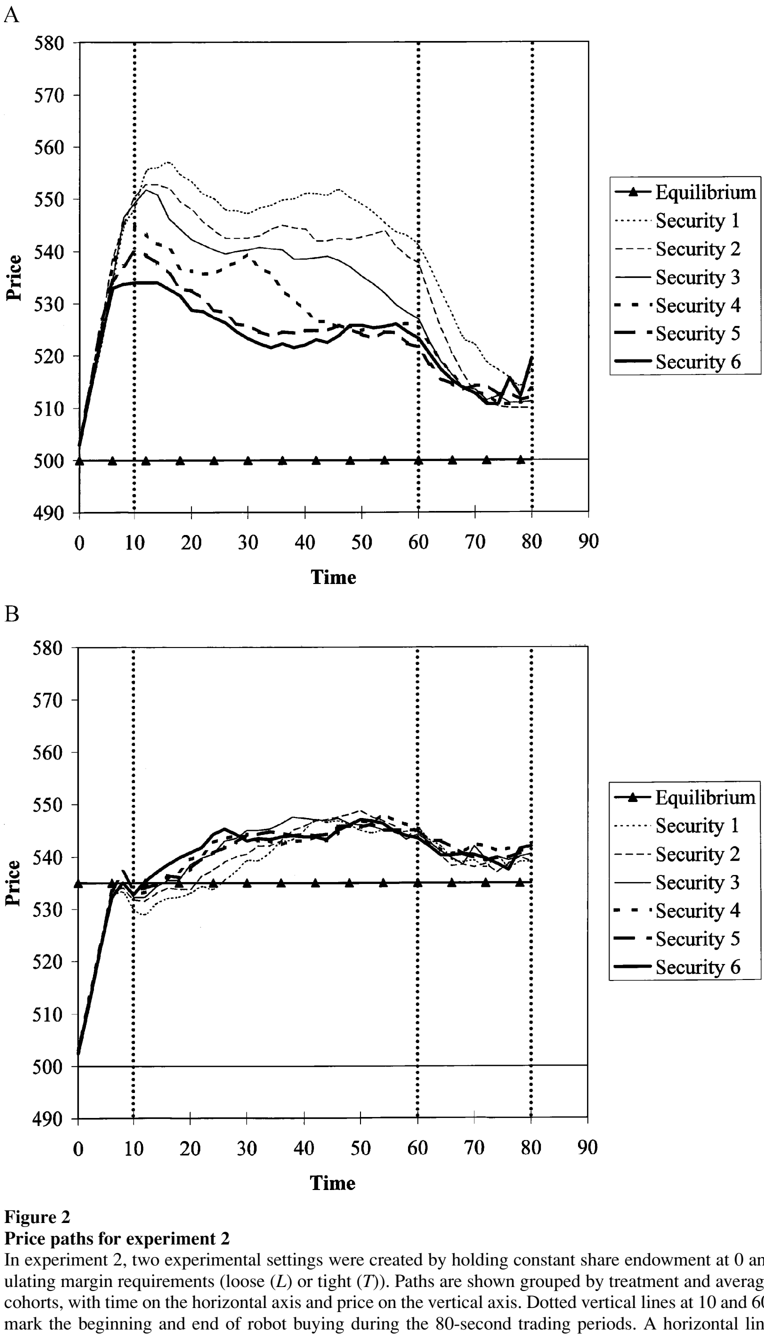

Figure 2
Price paths for experiment 2
In experiment 2, two experimental settings were created by holding constant share endowment at 0 and manipulating margin requirements (loose (L) or tight (T)). Paths are shown grouped by treatment and averaged across cohorts, with time on the horizontal axis and price on the vertical axis. Dotted vertical lines at 10 and 60 seconds mark the beginning and end of robot buying during the 80-second trading periods. A horizontal line labeled "Equilibrium" in the key indicates the equilibrium price in each setting. The other security numbers in the key indicate the order in which securities were traded. Panel A: Treatment 0L (0-share endowment, loose-margin limits). Panel B: Treatment 0T (0-share endowment, tight-margin limits).

Table 3
Deviation from equilibrium in experiment 2

	1	2	3	4	5	6	Average
			Panel A				
0L	40.81	36.15	32.33	28.05	24.46	23.17	30.82
0T	3.32	4.44	5.23	5.33	5.50	5.33	4.86
Average	22.07	20.29	18.78	16.69	14.98	14.25	

Source	Type III SS	Mean square	*F*-value	*p*-value
			Panel B	
Margin	4254.32	4254.32	141.04	0.00
Rep	321.42	64.28	16.06	0.00
Margin * rep	361.20	72.24	10.15	0.00

Panel A of this table provides information on primary dependent variable defined as the average deviation of the actual price path from the equilibrium price path per second. We calculate the area between the actual and equilibrium price path using the trapezoidal rule. Therefore the area between the two price paths is given by

$$\sum_{i=1}^{n} \frac{1}{2} \times h \times [f((a+(i-1)h)+f(a+ih)],$$

where h is 0.1 s and f is the difference between the actual and equilibrium price at any given time, $a = 0$ and $n =$ number of seconds in trading period/0.1. The columns 1–6 are the replications with 1 being the earliest replication and 6 being the latest. 0T refers to the setting with a share endowment of 0 and tight-margin limits (the minimum equity ratio is 0.6666, so traders may trade on margin as long as their equity-to-assets ratio is no less than .6666). 0L refers to the setting with share endowment of 0 and high loose margin (the minimum equity ratio is 0.3333, so traders may trade on margin as long as their equity-to-assets ratio is no less than 0.3333). Average reflects the average of the various columns/rows. Panel B provides results of the repeated measures ANOVA with the average deviation per second as the dependent variable. Margin is 1 in the loose-margin setting (0.3333) and 0 in the tight-margin setting (0.6666). Rep is the replication number and takes a value of 1 through 6.

effect of greater experience, more time after the end of robot trading, and more "cushion" in the minimum equity ratio.

3.2.1 Deviations from equilibrium price paths For a more detailed analysis of deviation from equilibrium, we compute the average per-second signed distances from equilibrium using the trapezoidal method described in the analysis of experiment 1. As in our first experiment, we focus on the entire price path rather than just the closing price (so that we can capture front-running and delayed arbitrage), and use repeated-measures analyses to assess statistical significance of treatment effects. As shown in Table 3, panel A, the per-second signed deviation from the upper bound of the equilibrium over all replications are substantially higher in 0L than in 0T (30.82 versus 4.86). As shown in Table 3, panel B, the main effect of margin is strongly significant ($p < 0.01$).

Table 3, panel A, also shows strong evidence that margin risk affects convergence to equilibrium. Though price errors in 0L drop from 40.81 to 23.17, there is no significant change in price errors for the last three repetitions in this setting ($p = 0.27$). The tight-margin setting shows little movement toward equilibrium, in large part, because markets in that setting start so close to equilibrium.

Table 4
Winnings in experiment 2

	1	2	3	4	5	6	Average
			Panel A				
0L	28.14	25.61	22.12	18.12	14.76	13.93	20.45
0T	0.68	1.79	2.24	1.62	0.89	2.29	1.59
Average	14.41	13.70	12.18	9.87	7.83	8.11	

Source	Type III SS	Mean square	*F*-value	*p*-value
			Panel B	
Margin	8087.12	8087.12	164.27	0.00
Rep	377.13	75.42	24.58	0.00
Margin * rep	585.74	117.15	28.77	0.00

Winnings refer to the difference between the liquidating value of a trader's position (including cash) and the initial endowment of cash and shares. Panel A provides information on the average winnings per trader per second across the two treatments and six repetitions. Panel B provides results of the repeated measures ANOVA with the average winnings per trader per second in each trading round as the dependent variable. 0T refers to the setting with a share endowment of 0 and tight-margin limits (the minimum equity ratio is 0.6666, so traders may trade on margin as long as their equity-to-assets ratio is no less than .6666). 0L refers to the setting with a setting with share endowment of 0 and high loose margin (the minimum equity ratio is 0.3333, so traders may trade on margin as long as their equity-to-assets ratio is no less than 0.3333). Margin is 1 in the loose-margin setting (0.3333) and 0 in the tight-margin setting (0.6666). Rep is the replication number and takes a value of 1 through 6.

3.2.2 Profits Table 4, panel A, summarizes results from the analysis of trader profits. The results are largely consistent with those of Table 3. Profits average \$20.45 in 0L, versus \$1.59 in 0T. The main effect of margin is statistically significant ($p < 0.01$). Profits show a learning pattern similar to that of price deviations. Profits drop in 0L, falling from \$28.14 above equilibrium winnings of \$0 in the first repetition, to \$13.93 above equilibrium in the last repetition; however, there is no significant change in profits in the last three repetitions in this setting ($p = 0.56$). These results further confirm our prediction that margin risk interferes with traders' willingness to discipline excessive front-running. Specialist profits are relatively small in both settings (\$5.75 per trade in 0T, \$1.38 in 0L), reflecting the specialists' ability to capture the bid-ask spread, and, in the 0T setting, specialists' selling of shares above fundamental value, and holding those positions until trade ends.

4. Summary

Relaxing margin requirements typically reduces equilibrium overpricing by allowing arbitrageurs to short sell more aggressively. However, we show in two laboratory "smart-money" experiments that relaxing margin requirements also slows convergence to equilibrium, and can increase the degree of overpricing observed among experienced traders, even though it reduces the equilibrium level of overpricing.

Our results are driven by two factors. First, arbitrage in markets is a social dilemma like the prisoners' dilemma: traders collectively earn far greater profits by front-running the sentiment trader and delaying arbitrage of price errors than they earn in equilibrium. Based on the results of many experiments investigating social dilemmas, we expected to see front-running and arbitrage in early trials of the smart-money game. Second, traders who attempt to exploit these deviations from equilibrium may experience a margin call if other traders continue to drive up prices. This “margin risk” can stall convergence to equilibrium, and allow overpricing to persist. Results of two experiments confirm that (1) early trials of trade in each setting exhibit the price bubbles that arise when traders front-run the sentiment trader and then delay arbitrage, and (2) convergence to equilibrium is dramatically slowed by limiting share endowments and loosening margin restrictions, because these conditions exacerbate the margin risk that traders face if they attempt to exploit deviations from equilibrium.

Our results suggest that models of arbitrage may need to consider risks that arise in disequilibrium outcomes. In the normal equilibrium characterization of our model (with traditional assumptions about rationality (including common knowledge of rationality)), the equilibrium price path is unique, and traders are therefore able to predict price movements with perfect accuracy. However, relaxing the traditional equilibrium assumptions introduces uncertainty about price movements, which hinders arbitrage. Future research could attempt to model this relaxation of traditional equilibrium assumptions in some formal way (perhaps by assuming that rationality is not common knowledge).

Future research could also examine the behavior of human dealers. Our experiments included a robot specialist who set bid and ask prices according to a mechanical model that was linear in cumulative net demand. This approach, also used in Hong and Stein (1999), allows our specialist to earn positive profits. Future research might explore how competing human dealers might alter our results. We suspect that if (unlike in our study) the dealers had limited capital and margin constraints (as do our smart traders), our results would be little changed, for dealers would face the same type of margin risk as our smart traders, and limit their arbitrage for the same reasons. However, a careful study of dealer behavior would probably need to incorporate some uncertainty in fundamental value, so that dealers would face the types of informational disadvantages they do in most microstructure models (Glosten and Milgrom, 1985; Kyle, 1985).

Because we are unable to provide our participants with unlimited opportunities for repetition, we are unable to determine whether traders would ultimately converge to equilibrium even when margin risk inhibits learning. However, learning in real markets would be less likely to encourage convergence to equilibrium than our markets, which provide a well-specified and unchanging environment with perfect feedback and an unchanging set of traders. As a result, we believe that factors that slow learning in our markets seem likely to have similar effects in real markets.

Interestingly, we find that synchronization risk by itself does not inhibit convergence to equilibrium, even though it confronts traders with the possibility of opportunity costs if they begin arbitrage substantially earlier than other traders. One possibility is that margin risk alters the variance in returns to arbitrage. Another possibility is that traders are more concerned about the possibility of out-of-pocket losses (as opposed to a missed opportunity for gains). Our results are therefore consistent with behavioral models of loss aversion (Kahneman and Tversky, 1979).

Appendix A: Calculation of Equilibrium Price Paths

In this appendix we identify equilibrium price paths for various important cases of smart-money game parameterizations, and calculate numerical price paths for the specific parameters used in experiments 1 and 2. We divide our analysis into three cases.

Case 1: $R^* = 1$. If the minimum equity ratio (R^*) is 1, then traders can sell only as many shares as they are endowed with. Given that the robot sells N shares every second for a total of T seconds, the N traders can discipline prices completely by each selling T shares. They will never choose to sell more than T shares, so the equilibrium closing price is $V + d^* = \text{Max}(V, T - Q(0))$. As long as traders begin with enough cash to purchase d^* shares in period 0, the equilibrium price path is constant at $V + d^*$. Otherwise, traders purchase as many shares as they can afford in period 0, allow the price to rise to $V + d^*$, and then begin selling shares to maintain a steady price at $V + d^*$. This case arises in both tight-margin settings in experiment 1, in which $T = 80$ and $R^* = 1$. Calculations show that $d^* = 0$ when $Q(0) = 90$, and $d^* = 70$ when $Q(0) = 10$.

Case 2: $R^* < 1$ and $(C(0) + Q(0)V)/(C(0) + Q(0)V + TV) \geq R^*$. The numerator on the left-hand side of the inequality is a single trader's equity at the beginning of trade, which also represents the trader's equity at the end of trade if prices remain at V throughout trading (because the trader never has the opportunity to gain or lose money). The denominator is the trader's closing assets. In this case, traders have sufficient capital to sell as many shares as the sentiment trader buys, and prices never deviate from V. This case arises in the loose-margin/high-endowment cell of experiment 1, in which $C(0) = 45{,}000$, $Q(0) = 90$, $R^* = 0.6$, and $T = 80$. This case also arises in the loose-margin setting of experiment 2, in which $C(0) = 15{,}000$, $Q(0) = 0$, $R^* = 1/3$, and $T = 50$.

Case 3: $R^* < 1$ and $(C(0) + Q(0)V)/(C(0) + Q(0)V + TV) < R^*$. In this case, the traders lack the capital to maintain a price of V throughout trading. As in case 1, if traders begin with enough cash to purchase d^* shares in period 0, the equilibrium price path is constant at $V + d^*$. Otherwise, traders purchase as many shares as they can afford in period 0, allow the price to rise to $V + d^*$, and then begin selling shares to maintain a steady price at $V + d^*$. To calculate the equilibrium prices, we assume (as in our experiment) that traders have sufficient access to cash to purchase d^* shares. In this case, traders' ending equity is equal to their starting equity of $C(0) + Q(0)V$ plus $Q(0)d$ earned in period 1 due to the increase in value of their initial share endowment, along with an additional $d/2$ profit on each of the d shares that they buy, at an average price of $d/2$. This level of equity never changes from period 1 to T, because prices do not change. Therefore, each trader's equity in period T is given by $E(T) = C(0) + Q(0)(V + d) + 0.5d^2$. Each trader's assets at the end of trade are given by $A(T) = C(0) + T(V + d) - d(V + d/2)$. (We know the trader has no shares, or the equilibrium price would be lower. The trader has his initial cash endowment; the cash proceeds from selling T shares at a price of $V + d$ less the cash used to buy d shares at a price of $V + d/2$.) Because the minimum equity ratio must be binding when $d^* > 0$, we know that d^* must be the value of d that satisfies the requirement $E(T)/A(T) = R$. This case arises in the loose-margin/low-endowment setting in experiment 1, with $C(0) = 45{,}000$, $Q(0) = 10$, $R = 0.6$, and $T = 80$. Solving the requirement implies that $d^* = 4$. This case also arises in the tight-margin setting of experiment

2, with $C(0) = 15{,}000$, $Q(0) = 0$, $R = 2/3$, and $T = 50$. Solving the requirement implies that $d^* = 35$.

Appendix B: Instructions for Experiment One

B.1 Overview
During this session, you will trade shares in 24 securities (one at a time) for 90 seconds each. Your gains and losses from the session will be denominated in "laboratory dollars." After trading shares in all securities, we will ask you a series of questions about your experience. The entire session should take about 90 minutes. Please do not talk with other subjects, look at others' computer screens, or leave the room without explicit permission from the experiment administrator.

B.2 Liquidating dividend
Every security you trade will pay a dividend of $500 after the end of the 90-second trading period. If you own the share, you receive the dividend. If you owe the share to someone else (because you have sold more shares than you originally owned), you will have to pay the $500 to the buyer.

B.3 Market price
When you buy and sell shares, you will be trading with a computerized *dealer*. The dealer will sell you shares at $1 above market price (the *ask* price), and will buy shares at $1 below market price (the *bid* price). The *market price* rises when traders are buying more than they are selling (the "trade imbalance" is positive), and falls when traders are selling more shares than they are buying (the "trade imbalance" is negative). The market price always starts at 500, and moves up or down by $1 every time the trade imbalance reaches a critical level. The "critical trade imbalance" necessary to move price by $1 is equal to the number of human traders in the market. (You will be told the number of human traders in the market, and that number will not change).

B.4 Robot trader
There is a robot trader that will buy enough shares to move the price up by $1 every second, starting 5 seconds into the trading period, and continuing until 5 seconds before the trading period ends. The robot's trades affect prices just like any other trade. If no one else traded, price would rise from 500 to 580 in each market.

B.5 Your financial position
You start trading each security with shares and cash, but no debt. This initial endowment will vary from security to security, but for a given security every trader will always have exactly the same endowment.

For some securities, you will be allowed to borrow money to buy shares (debt) and borrow shares to sell them ("short selling"). Your "equity" is determined by your assets (cash and shares you hold) minus your liabilities (debt and shares you have sold short). For the purposes of computing your financial position, the value of a share is determined by the current market price.

For some securities, you will be allowed to borrow money and shares, as long as your "equity ratio," defined as equity/assets, does not fall below 0.60. The computer will not allow you to make trades that would violate your equity ratio limit. If you own shares, a price decrease might cause you to violate the limit. If you have sold shares short, a price increase might cause you to violate the limit. Whenever this happens, your computer will automatically sell enough of the shares you own, or buy back enough of the shares you have sold short, in order to bring the equity ratio back to 0.80.

B.6 Making money

There are two ways to generate trading gains in this market:

- Buy a share and then sell it for more than you paid.
- Sell a share and then buy it back for less than you paid.

You can implement these strategies using very short holding periods (for example, selling a share and buying it back very quickly), or longer holding periods (for example, selling a share and buying it back after waiting for a while). The longest holding period would entail buying or selling a share and holding it until the liquidating dividend is paid, so that you would close out your position at $500.

B.7 How to trade

You can trade shares by buying or selling, as follows:

- Click the "Buy 1" button to buy one share at the ask price ($1 above the market price).
- Click the "Sell 1" button to sell one share at the bid price ($1 below the market price).

B.8 Information spreadsheet

The spreadsheet in the upper center of the screen contains information regarding your trades, as well as information regarding market activity. Key information includes the following:

- How many shares you have bought and sold, as well as how many shares in total have been bought and sold by all traders in the market (including yourself and the robot trader)—for this security.
- Your share holdings.
- Your a*verage share cost/revenue*, which indicates the average you paid or received for each share you hold ("Average Share Cost" if your share balance is positive or "Average Share Revenue" if your share balance is negative). This line shows "na" if your share balance equals 0. The average cost of shares you hold when trade begins is 500.
- The current market price.
- Your cash held or your debt.
- The current market value of any shares you own or have sold short.
- Your total assets (cash held plus the current market value of shares you own) and your total liabilities (debt plus the current market value of shares you have sold short).
- Your equity (assets less liabilities).
- Your equity ratio (equity/assets).

B.9 Market information charts

The chart at the lower right-hand corner of the screen shows market prices, trading volume, and bid-ask spreads over time. You can adjust the time interval aggregation on the chart (from 1 to 20 seconds). To get an updated chart, click the "Reset chart" button.

B.10 Converting laboratory dollars into USD

Every dollar you gain will increase your cash payment. Losses will decrease your cash payment, down to a minimum of $5. We expect the average payment to be about $25 for this session. The gains and losses of other people in your market have no effect on your payment. Therefore, you should focus solely on increasing your own profits and reducing your own losses.

Appendix C: Instructions for Experiment 2 (That Differ from Experiment 1)

C.1 Robot trader

There is a robot trader that will buy enough shares to move the price up by $1 every second whenever it is trading.

- The robot trader will start buying 10 seconds into trading and will buy for 50 seconds. In these markets, if no one but the robot traded, price would go from 500 to 550.

C.2 Your financial position

You start trading each security with $15,000 cash and no shares. You can borrow cash or shares, subject to the following limitations:

- In half of the markets, if your equity ratio drops below 0.3333 your computer will automatically sell enough of the shares you own, or buy back enough of the shares you have sold short, to bring your equity ratio above 0.6666.
- In the other half of the markets, if your equity ratio drops below 0.6666 your computer will automatically sell enough of the shares you own, or buy back enough of the shares you have sold short, to bring your equity ratio above 0.8333.

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