



The Neural Inhibition of Learning Increases Asset Market Bubbles: Experimental Evidence

Levan Efremidze, George Sarraf, Karen Miotto & Paul J. Zak

To cite this article: Levan Efremidze, George Sarraf, Karen Miotto & Paul J. Zak (2017) The Neural Inhibition of Learning Increases Asset Market Bubbles: Experimental Evidence, Journal of Behavioral Finance, 18:1, 114-124, DOI: [10.1080/15427560.2016.1238372](https://doi.org/10.1080/15427560.2016.1238372)

To link to this article: <https://doi.org/10.1080/15427560.2016.1238372>



Published online: 08 Feb 2017.



Submit your article to this journal [↗](#)



Article views: 150



View related articles [↗](#)



View Crossmark data [↗](#)

The Neural Inhibition of Learning Increases Asset Market Bubbles: Experimental Evidence

Levan Efremidze ^{a,b}, George Sarraf^{b,c}, Karen Miotto^d, and Paul J. Zak^{b,e}

^aPepperdine University; ^bCenter for Neuroeconomics and Department of Economics, Claremont Graduate University; ^cUniversity of California, Irvine; ^dUniversity of California, Los Angeles; ^eLoma Linda University Medical Center

ABSTRACT

The authors tested a leading theory of bubble formation, insufficient learning, in a laboratory asset market using a drug, Naltrexone, which inhibits reinforcement learning. We found that asset price bubbles in Naltrexone sessions were larger compared with placebo sessions, averaging 60% higher in amplitude and 77% larger in the deviation from fundamental value in the final 12-period trading round. There was no difference between conditions in understanding of the trading rules, overconfidence, or confusion. Participants on Naltrexone appeared unable to determine appropriate trading strategies as prices changed. The findings indicate that specific neural mechanism of reinforcement learning is involved in the formation of asset market bubbles.

KEYWORDS

Bubbles; Asset pricing;
Neurofinance; Naltrexone;
Behavioral finance;
Neuroeconomics

Introduction

The deflating U.S. real estate bubble of 2007 and subsequent 42% stock market decline in August–November 2008 eliminated \$14 trillion of wealth. The burgeoning Internet companies in the 1990s led to multibillion-dollar valuations for companies that only produced “vaporware.” Many of these startups disappeared with the dot-com bust in March 2000. From 1982 to 1996, the Dow Jones Industrial Average quadrupled its value with Alan Greenspan, then Federal Reserve Board chairman, ascribing this rise to “irrational exuberance.” Even the Dutch tulip bulb bubble of 1637 saw prices rise 1,000% only to fall to nearly zero a year later. Asset market bubbles are not new and appear not to be going away, as there are new claims about existing or rising bubbles (Shiller [2014]). The refrain heard as assets surge in value is “this time is different.” The collapse of bubbles incites calls for more regulation of asset markets to reduce asset price whipsawing.

Bubbles arise when the price of an asset exceeds its fundamental value. The fundamental value of a stock is the discounted value of dividends that accrue to its owner. Whether a bubble exists depends on how expected changes in fundamental value are measured. Rational expectations models either exclude the possibility of a bubble by ascribing price changes to unobserved changes in fundamental factors (Flood and Garber [1980]), or

allow their existence under highly restricted conditions (Blanchard [1979], Tirole [1982], Santos and Woodford [1997]). Behavioral finance models, borrowing from psychology, posit that bubbles can be caused by systematic cognitive biases of investors (Barberis and Thaler [2002], Daniel, Hirshleifer and Teoh [2002], Hirshleifer [2001], Scheinkman and Xiong [2003]). Empirical studies show that credit expansion (e.g., Okina, Shirakawa and Shiratsuka [2001], Allen and Gale [2000], Allen [2005]), and inexperienced traders (e.g., Greenwood and Nagel [2009]) contribute to bubble formation.

Another way to test the sources of bubbles is to trade assets in a laboratory. In experiments in which participants trade assets for money, bubbles readily appear and controlling for factors such as capital gains taxes, short selling, and transactions fees does not eliminate them (Smith, Suchanek and Williams [1988], Dufwenberg, Lindqvist and Moore [2005], Hussam, Porter and Smith [2008], Deck, Porter and Smith [2014]). Bubbles reliably appear in experiments that use identical portfolios, or subpopulations of students, corporate managers, or professional traders (Smith, Suchanek and Williams [1988], King et al. [1993], Haruvy, Lahav and Noussair [2007]). Introducing short selling reduces bubbles and in some cases shows underpricing (Haruvy and Noussair [2006]). Permitting margin buying or higher starting cash endowments

CONTACT Levan Efremidze  levan.efremidze@gmail.com  Department of Finance, Graziadio School of Business and Management, Pepperdine University, 24255 Pacific Coast Highway, Malibu, CA 90263.

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/hbhf.

© 2017 The Institute of Behavioral Finance

produces larger bubbles (King et al. [1993], Caginalp, Porter and Smith [2000], Haruvy, Lahav and Noussair [2007]). Smaller bubbles are formed in experiments with futures markets and when transaction prices are constrained to be closer to fundamental value in initial trading (Porter and Smith [1995], Caginalp, Porter and Smith [2000], Noussair and Tucker [2006]), but they still occur. Reducing confusion about fundamental values or strategic uncertainty about the behavior of others have been shown to reduce bubbles in asset markets (Kirchler, Huber and Stöckl [2012], Huber and Kirchler [2012], Akiyama, Hanaki and Ishikawa [2013], Cheung, Hedegaard and Palan [2014]).

As participants learn throughout the periods and rounds of trading assets in laboratory markets, the size of bubbles tends to decline (Dufwenberg, Lindqvist and Moore [2005], Akiyama, Hanaki and Ishikawa [2013]), or disappear (Hussam, Porter and Smith [2008]). Yet even for experienced traders, changes in economic fundamentals such as the size of initial endowments and dividend uncertainty cause bubbles to rekindle (Hussam, Porter and Smith [2008]). In typical laboratory experiments, convergence of prices to fundamental value takes place when participants learn through trading experience in a stable market environment. The terms *experience* and *learning* are interchangeably used in the experimental asset market literature (Hussam, Porter and Smith [2008]) and refer to improved trading behavior after learning through several rounds of trading experience.

Learning allows traders to observe patterns of prices, liquidity, and other trading variables to forecast what others are doing and adjust their trading strategies. Smith, Suchanek and Williams [1988] reported that this process involves trial-and-error learning. Nevertheless, the role of trial-and-error learning in the formation and maintenance of bubbles has not been tested by exogenously controlling learning itself. The emerging field of neuroeconomics has applied neuroscience techniques to characterize the brain basis for financial and economic decisions (Zak [2004], Montague [2007]). A number of neuroeconomics studies have used various neural and physiological measures during financial decisions to understand how effective decisions are made (Lo and Repin [2002], Knutson and Bossaerts [2007], Sapra, Beavin and Zak [2012]). The role of learning in asset market bubbles can be tested neurologically as well.

In this study, we tested the role of learning in bubble formation and persistence in a laboratory asset market by exogenously altering the ability of healthy human beings to learn. We used a drug, Naltrexone, which inhibits reinforcement learning, and then compared bubble attributes to sessions in which participants have taken a placebo. A large number of neuroeconomics studies

have shown that the ventral striatum brain region, which is a key target for the neurotransmitter dopamine, activates during the anticipation of monetary rewards (Knutson and Bossaerts [2007]). This area of the brain focuses an organism's attention on possible rewards in the environment and facilitates reinforcement learning by activating when expected outcomes differ from actual outcomes (Schultz, Dayan and Montague [1997]). Humans share this reward-learning brain system with nearly all lower animals, including fish. Acquiring resources is essential to every species' survival and reproduction, and therefore has deep evolutionary roots. The neurotransmitter dopamine has several roles in the brain and body, including motivating attention to new information in the environment by providing the organism with a pleasurable experience. This reward-for-learning response is the same that occurs during sex and that is hijacked by drugs of abuse such as cocaine and methamphetamine (Bostwick and Bucci [2008]). The brain's reinforcement learning system is more immediate and mechanistically different than short-term working memory or the brain's storage of long-term memories (Hyman [2005]).

Naltrexone is included in a class of drugs called opioid antagonists that inhibit the binding of dopamine in the ventral striatal region of the brain (Benjamin, Grant and Pohorecky [1993], Ramsey, Gerrits and Van Ree [1999]). Naltrexone thereby reduces conditioned reinforcement learning (Liu et al. [2009]). The value of using Naltrexone to inhibit learning, rather than using experienced and inexperienced traders, is that Naltrexone uniformly inhibits learning for participants receiving it (subject to individual variations in metabolism, but these are small during a 2-hr experiment).

We hypothesized that, relative to placebo, asset market trading sessions in which participants received Naltrexone would result in sessions with larger bubbles. We also included a control condition in which participants were given caffeine. Caffeine has been shown to enhance learning (Smith [2002], Nehlig [2010]) and we hypothesized that bubbles would be smaller in this condition compared to placebo.

We chose not to use brain imaging techniques such as functional magnetic resonance imaging (fMRI) or electroencephalogram (EEG) that assess differences in activity by locations in the brain. Both fMRI and EEG studies are correlational, while using a drug to inhibit reinforcement learning provides causal evidence for a mechanism producing bubbles. In addition, some brain imaging studies suffer from circular reasoning regarding networks of brain activity correlated with a behavior, and some studies use inappropriate statistical techniques (Ramsey et al. [2010], Vul et al. [2009]). The use of

Naltrexone allowed us to test our specific hypothesis regarding the role of learning on bubbles neurologically without having to interpret the many aspects of brain activity that occur when people trade assets. While the use of drugs to alter brain activity is a reasonably new approach to understanding economic decisions, it is common in neuroscience (Zak [2004], Park and Zak [2007], Vercoe and Zak [2010]).

We found that bubbles formed in all three conditions (placebo, caffeine, Naltrexone), but were largest in the Naltrexone condition confirming our hypothesis. The general pattern of prices we found was similar to other asset trading experiments. Specifically, prices began below fundamental value then quickly rose to surpass it. Prices rapidly decline in later trading periods, converging toward fundamental value. Prices were similar across conditions during the initial two trading periods (each lasting 90 s), but started to diverge thereafter as reinforcement learning differentially affected trading strategies.

We also collected data on participants' overconfidence, possible confusion, and understanding of trading rules in order to test if Naltrexone affected more than just learning. There was no difference in any of these measures across treatments. In addition, we calculated the excess demand and total value of transactions (the product of the average transaction price and share turnover) and found no difference across conditions. We interpret these as evidence that the traders' general willingness to trade and earn money were not altered by Naltrexone. This evidence suggests that Naltrexone primarily inhibited reinforcement learning rather than affecting bubbles in some other way.

Earnings were same across conditions and men earned more than women in all treatments. We collected data on emotional lability and found it varied by gender and negatively correlated with earnings. This may explain the gender difference in trading profits. The proportion of women in a session did not influence the bubble size and was similar across conditions.

We compared our experimental data to typical financial market data by testing if volatility clustering occurred. We fit a parsimonious exponential generalized autoregressive conditional heteroskedasticity (EGARCH) model with asymmetric shocks to our laboratory stock returns, and included round dummies to test for learning effects. The learning/round dummies were insignificant in the Naltrexone condition, but asymmetric volatility shocks and turnover were significant predictors of asset returns. The latter two variables are typically found to be significant in U.S. financial data (Hiemstra and Jones [1994]).

Our research extends experimental asset markets studies that have shown that trading experience (under

normal learning conditions) reduces the magnitude and duration of price bubbles. We use a novel neuroeconomic approach to show that insufficient level of learning, which in effect can also be interpreted as inexperience, is a source of bubbles. By exogenously controlling the ability to learn using Naltrexone, we demonstrated that price bubbles, when compared to sessions in which participants received a placebo, are substantially larger. These results provide direct evidence that the reinforcement learning neural mechanism contributes to asset market bubbles. Our findings also contribute to the empirical finance literature by showing that asset prices in an experimental market exhibit asymmetric clustered volatility. This supports the relevance of the experimental approach when seeking to understand actual financial markets, as well as providing a way to test the effects of financial market regulations.

Experimental design

There were 178 participants ($M = 19.8$ years, $SD = 1.6$ years; 43% women, 54% Asian, 24% Caucasian, 8% Hispanic, other/no data 14%), all of whom provided written informed consent before participating (the Institutional Review Boards of UCLA and Claremont Graduate University approved this experiment). The market experiments were conducted on October 20, 22, and 27 and November 10 and 12, 2009, at the California Social Science Experimental Laboratory (CASSEL), a joint project of UCLA, Caltech, and the National Science Foundation. We conducted five sessions for the Naltrexone treatment, five sessions for the caffeine treatment, and three sessions for placebo. Each session consisted of three rounds, and each round comprised 12 periods of trading. After each period of 90 s, subjects were presented the data on last period dividend amount, their individual earnings and number of shares they owned.

Participants had a private medical screening to rule out those with major medical disorders, illicit drug or excess alcohol consumption during the previous 24 hours, and other contraindications.

After passing the medical screening, participants were randomly assigned to receive 50 mg Naltrexone ($n = 64$), 200 mg caffeine ($n = 70$), or placebo ($n = 42$). Titrating the dose of caffeine in drug studies requires identifying a dose that would increase alertness while at the same time not making participants jittery. Most studies use 200–300 mg doses of caffeine, equivalent to one to two cups of coffee. In a number of studies, doses of this size have little effect on behavior, presumably because of

caffeine acclimation in the general population (Einöther and Giesbrecht [2013]).

All substances were administered in identically appearing gelatin capsules with cellulose filler using a double-blind procedure. On debriefing, participants reported that they did not know which substance they had been given. No adverse effects were reported.

Each session included between 10 and 14 participants. All those in a session received the identical substance, assigned by a lab administrator who was not part of the experiment. This protocol allowed us to compare the effects of groups of participants with identical manipulations. Participants completed demographic, personality and attitudinal surveys for 60 min while the drugs loaded following published pharmacokinetics. These included a basic demographic survey and the Affective Intensity Measure (Larsen, Diener and Emmons [1986]).

After the drug loading period, we put participants into a standard (Smith, Suchanek and Williams [1988]) laboratory stock trading experiment in which software is used to post asks to sell stock and bids to buy stock. Participants were endowed with either six shares of stock and \$2.16, or two shares of stock and \$6.48 by random assignment. Both equal endowments and unequal endowments have been tried in asset market experiments, and bubble measures are not affected by the choice of this setup (King et al. [1993]). Unequal endowments (equal in value, but different in the proportion of cash to number of shares) were used to stimulate trading. The instructions informed participants that there were three trading rounds, with each round having 12 trading periods lasting 90 s each. After each trading period ended, stockholders earned either \$0.18 or zero for each share of stock held with a 50% chance of each outcome. Trades were executed when an offer to sell and a request to buy were accepted by both parties. The prices of executed transactions were shown to all participants. After 12 trading periods, a 1-min break was taken while participants completed a trading strategy survey. The process was repeated for each of the three rounds, totaling 36 trading periods. Participants were paid in cash at the end of the trading session.

The fundamental value of the stock is the summed expected value of the dividend times the number of remaining periods. That is, the fundamental value is the expected value of the flow of dividends one would receive from holding the stock. When period 1 starts, the fundamental value of a share of stock was \$1.08 ($\0.09×12); in period 2 fundamental value was \$0.99 and so on, going to \$0.09 in round 12. This setup thus produces declining pattern of fundamental value. It is commonly adopted in experimental asset markets. Constant fundamental values also have been tested in market

experiments and in most studies this change reduces bubbles (Noussair, Robin and Ruffieux [2001], Bostian, Goeree and Holt [2005], Kirchler, Huber and Stöckl [2012], Noussair and Tucker [2014], Stöckl, Huber and Kirchler [2014]).

After each round we asked participants about their confidence regarding their trading performance, how well they understood the rules of trading, and how confused they were. Overconfidence was measured by answering the question “Do you think that your performance, judged by the increase of your earnings, during this session was below average (1), average (2), or above average (3)?” Understanding of trading rules was based on the statement “Did not understand the rules of the game” on a 1–7 scale. Confusion was measured with the statement “Did not understand what I was doing” on a 1–7 scale.

Results

We used three standard measures of bubbles: amplitude (AMP), normalized average price deviation (NPD), and duration (DUR).¹ AMP is defined as the difference between the highest and lowest average per period price deviation from fundamental value divided by the initial fundamental value of the stock. The NPD is average per period absolute price deviation from fundamental value divided by the initial fundamental value. DUR is defined as the number of periods the average price deviation from fundamental value increases relative to the previous period.

As in other studies of asset trading, bubbles readily form and we replicate this finding in the placebo condition. For this treatment, prices are higher than fundamental value during the 12 trading periods of round 1 (R1: AMP: $M = 0.95$, $SD = 0.50$, $p = 0.07$; two-tailed Mann-Whitney U test [MWU]). The bubble remains in the second 12-period round (R2: AMP: $M = 0.68$, $SD = 0.25$, $p = 0.03$; Two-tailed MWU), while in the third 12-period round, average price converges toward fundamental value in the final three trading periods (R3: AMP: $M = 0.74$, $SD = 0.09$, $p = 0.02$; two-tailed MWU).

Testing the caffeine and placebo conditions for all measures of bubbles in R1 showed no difference (AMP: $p = 0.99$; NPD: $p = 0.99$; two-tailed MWU). Similar results were found for R2 and R3 (R2: AMP: $p = 0.99$; NPD: $p = 0.77$; R3: AMP: $p = 0.99$; NPD: $p = 0.99$; see Table 1). The dose of caffeine given was equivalent to a strong cup of coffee. Because most people ingest caffeine daily, our tests showed that amount of caffeine did not affect behavior. Other studies also find no effect (Einöther and Giesbrecht [2013]). In future research, other method should be devised to increase learning in market experiments exogenously. As a result, the placebo

Table 1. Comparisons of treatment averages using various measures of bubbles.

	Amplitude	Normalized Average Price Deviation	Duration
Mean of Each Measure			
N Sessions			
Round 1 mean	1.924	0.896	4.600
Round 2 mean	1.151	0.886	6.000
Round 3 mean	1.183	0.641	5.800
P Sessions			
Round 1 mean	1.024	0.393	5.625
Round 2 mean	0.684	0.341	6.750
Round 3 mean	0.739	0.363	7.875
Wilcoxon/Mann-Whitney Rank-Sum Tests			
Placebo and Caffeine treatment comparisons			
p Round 1	1.000	1.000	1.000
p Round 2	1.000	0.766	0.880
p Round 3	1.000	1.000	0.645
N and P session comparisons			
p Round 1	0.067	0.023	0.603
p Round 2	0.016	0.034	0.824
p Round 3	0.092	0.213	0.237
Permutation Tests of Paired Replicates			
Round 1 and Round 3 comparisons within each treatment			
N Sessions p	0.126	0.000	0.000
P Sessions p	0.060	0.500	0.171

There is no statistical difference between caffeine and placebo sessions so these were combined in the P treatment. Comparing N and P treatments shows Naltrexone caused larger amplitude and normalized average price deviation bubbles in R1 and R2, but not in R3. There was no difference in bubble duration across treatments.

and caffeine conditions were combined into one that we will call the P sessions.

Comparing the Naltrexone (N) sessions to the P sessions, there is no difference in prices for the first two trading periods but prices start to diverge afterwards (mean price differences: Period 1 $p = 0.61$; Period 2 $p = 0.83$; Period 3 $p = 0.09$; Period 4 $p = 0.09$; Period 5 $p = 0.02$; two-tailed MWU). This will be discussed further in this section.

The average price in the N sessions continues to exceed that of the P sessions until the 35th of 36 trading sessions. In the 12 trading periods of R1, N sessions had bubbles of larger amplitude and normalized average price deviation than in the P sessions (AMP: N session $M = 1.92$, P session $M = 1.02$, $p = 0.03$; NPD: N session $M = 0.90$, P session $M = 0.39$, $p = 0.01$; one-tailed MWU). During R2, bubbles for N sessions remained larger relative to P sessions with higher amplitude and normalized average price deviations (AMP: N session $M = 1.15$, P session $M = 0.68$, $p = 0.01$; NPD: N session $M = 0.89$, P session $M = 0.34$, $p = 0.02$; one-tailed MWU).

In R3, the bubble began to deflate in the P sessions, with P treatment amplitude in R3 marginally smaller than for P treatment R1 (AMP: R1 $M = 1.02$, R3 $M = 0.74$, $p = 0.06$, Permutation tests of paired

replicates (PTPR), $q = 8$). The normalized price deviation and duration were unchanged in the P sessions between R1 and R3 (NPD: R1 $M = 0.39$, R3 $M = 0.36$; $p = 0.50$, PTPR; DUR: R1 $M = 5.62$, R3 $M = 7.88$; $p = 0.17$, PTPR). This pattern was not observed in the N sessions. For the Naltrexone treatment, the average amplitude of the bubble fell between R1 and R3 but the change was not statistically significant (AMP: R1 $M = 1.92$, R3 $M = 1.18$, $p = 0.13$). At the same time, the bubble duration of the N sessions increased from R1 to R3 (R1 $M = 4.60$, R3 $M = 5.80$, $p < 0.001$, PTPR), although the NPD fell (R1 $M = 0.89$, R3 $M = 0.64$, $p = 0.001$; Figure 1).

Next we investigated other differences between the P and N sessions. Economic theory indicates that the correct pricing of an asset requires sufficient trading volume (Lo, Mamayasky and Wang [2004]). We first examined the turnover (TURN) of shares. TURN is defined as the number of transactions in a period divided by the number of outstanding shares. Naltrexone did not affect initial trading activity, as turnover was similar across N and P sessions during first three periods of trading (TURN: Period 1 $p = 0.19$, Period 2 $p = 0.09$, Period 3 $p = 0.16$, Period 4 $p = 0.07$; two-tailed MWU). The turnover series start to diverge in subsequent periods. As starting prices and turnover were similar across conditions, this indicates that traders started with similar preferences to trade, but once sufficient learning occurred (specifically, after the third period), participants started trading differently. A manifestation of the learning difference was decreased turnover in Naltrexone sessions. Turnover was lower in the 36-period N sessions compared to the 36-period P sessions (P: $M = 0.47$, N: $M = 0.28$, two-tailed paired t test $p < 0.001$). Participants in the N sessions also showed lower turnover in R3 compared to R1 (R1 = 4.13, R3 = 2.56; $p = 0.001$) while turnover was statistically unchanged in the R1 versus R3 in the P sessions (R1 = 6.04, R3 = 5.29, $p = 0.22$). Previous studies have found both positive and negative relationships between price bubbles and turnover, both in experimental markets (Smith, Suchanek and Williams [1988], Camerer [1992], Lo, Mamayasky and Wang [2004]), and actual markets (Hong and Sraer [2011]). In our experiment, larger bubbles are associated with lower trading volume. We discuss this further in this section.

We also tested the generalizability of our results to financial markets by examining if the volatility clustering of asset prices found in actual financial markets (Hiemstra and Jones [1994]) also occurred in our laboratory market. Using a Box-Jenkins methodology, standard autoregressive moving average models produced serially correlated residuals indicating volatility persistence. For this reason, we fit a parsimonious generalized

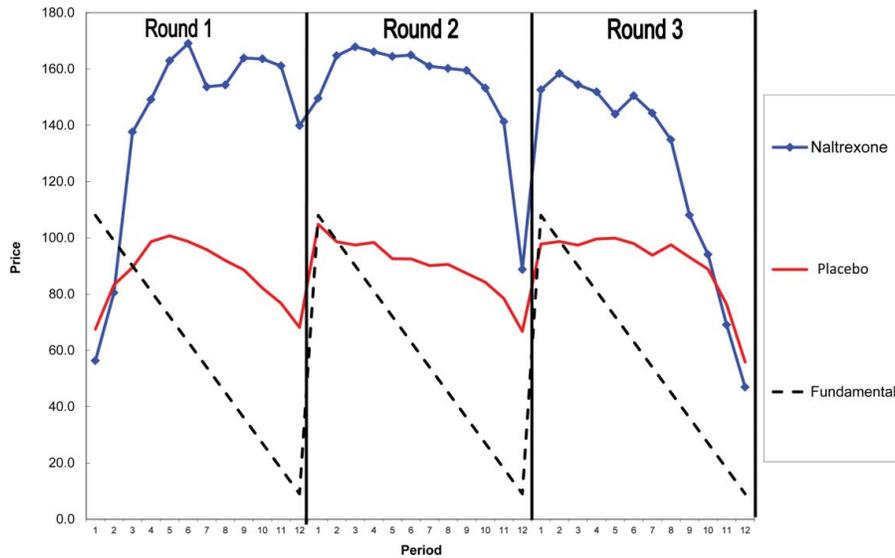


Figure 1. Average prices per period in Naltrexone and placebo sessions. The Naltrexone sessions (line with markers) have bubbles that are larger than those in the placebo sessions (solid line) over 36 periods as measured by amplitude (R1: 88% higher, $p = 0.034$; R2: 68% higher, $p = 0.008$; and R3: 60% higher, $p = 0.046$), and normalized average price deviation (R1: 128% higher, $p = 0.012$; R2: 260% higher, $p = 0.017$; and R3: 77% higher, $p = 0.105$). Average asset prices for the Naltrexone group converge to the placebo prices after 33 trading periods but still remain above fundamental value.

autoregressive conditional heteroskedasticity (GARCH) model of stock returns (expressed as the difference of log prices) with 2 lags of turnover as explanatory variables, and with round dummies to test for learning effects.

We included an ARCH-in-mean term in the variance and EGARCH asymmetric shock (Bollerslev, Engle and Nelson [1986]) with the following form:

$$R_t = \eta + X_t \gamma + \sigma_t^2 + \varepsilon_t \tag{1}$$

$$\ln(\sigma_t^2) = \omega + \alpha \varepsilon_{t-1}^2 / \sigma_{t-1}^{0.5} + \lambda |\varepsilon_{t-1}^2 / \sigma_{t-1}^{0.5}| \tag{2}$$

$$\varepsilon_t \sim N(0, \sigma_t^2)$$

where X_t includes two lags of turnover, an interaction term indicating R2 and the first lag of turnover, and a R3 indicator; σ_t^2 is the conditional variance of stock returns; and $\eta, \omega, \gamma, \lambda,$ and α are parameters to be estimated. The estimation was made by maximum likelihood. Equation 1 has ARCH-M specification with a conditional variance term. Equation 2 is an EGARCH(0,1) specification that captures asymmetric response of conditional variance to lagged shocks.

The same model was found to fit both the P and N treatments, resulting in white noise residuals. The EGARCH asymmetric coefficients are significant for both treatments (P sessions: $p = 0.001$; N sessions: $p = 0.05$). This model shows that asymmetric volatility shocks and turnover affect asset returns in our laboratory asset market as they do in the actual financial markets (P sessions TURN lag 1: coefficient = 0.38, $p = 0.001$;

TURN lag 2 coefficient = 0.25, $p = 0.001$; N sessions TURN lag 1: coefficient = 1.61, $p = 0.001$; TURN lag 2 coefficient = -0.92, $p = 0.06$; see Table 2).

We tested learning level in the EGARCH model with R3 dummies. The learning coefficient (R3 dummy) was insignificant in the N sessions, but positive and significant in the P sessions (see Table 2). This is evidence of higher learning level in the placebo group.

Figure 1 shows average prices, and it is easy for an eye to detect absolute overvaluation in general in Naltrexone treatment, but it does not show sampling variation within treatment and price dynamics across different rounds. For the learning within and across the rounds in each treatment, we use various statistical tests. Overall analysis of the results suggests that there is less learning in N sessions than in P sessions. How much learning is in the Naltrexone treatment? We can say that with reduced reinforcement learning we diminished learning effects of the experience (with one dose of Naltrexone we most likely reduced learning, not completely shut it off). There is reduction of learning effects in bubble measures in the Naltrexone treatment, which is mostly demonstrated by extremely higher price peaks and amplitudes in all rounds, and in EGARCH results. There are still some lingering learning effects from R1 to R3 in the Naltrexone treatment, which show up in the NPD measure.

Let's focus now on the learning effects during the initial periods of trading and then throughout the whole experiment. The reinforcement learning system of

Table 2. Return dynamics using lagged turnover and EGARCH asymmetric volatility estimates.

Dependent Variable	P Sessions R_t		N Sessions R_t	
	Coefficient	SE	Coefficient	SE
GARCH	8.031*	3.379	13.250	8.360
Intercept	-0.375**	0.025	-0.339*	0.170
Turnover(t-1)	0.385**	0.000	1.607**	0.357
Turnover(t-2)	0.254**	0.045	-0.918***	0.488
Round 3 dummy (LEARNING)	0.040**	0.013	0.009	0.079
Round 2 dummy*Turnover(t-1)	0.111**	0.018	-0.084	0.182
<i>Variance equation</i>				
Intercept	-6.453**	0.487	-4.265**	0.239
RES /SQR[GARCH](1)	0.059	0.454	-0.455	0.380
RES/SQR[GARCH](1)	-1.574**	0.286	-0.771*	0.397
R^2	0.515		0.646	
Adj. R^2	0.331		0.512	
Log likelihood	50.604		28.970	
Durbin-Watson stat	2.274		1.667	
Akaike information criterion	-2.774		-1.331	
Schwarz criterion	-2.353		-0.911	
Observations after adjusting endpoints	30		30	

** and *** indicate significance at 1%, 5%, and 10%, respectively. The estimation was made by maximum likelihood. The positive and significant coefficient for the R3 dummy in the P sessions shows the effect of learning. This coefficient is not different than zero for the N sessions.

nucleus accumbens (NA) starts immediately (fast) (Dayan and Daw [2008]). It is rapidly activated in the initial periods of the trading experiment and is active throughout the whole experiment (Smith et al. [2014]) and signal strengths measured in the NA (using fMRI) across trading periods predict future period prices. The reinforcement learning mechanism does not work on absolutes, but on variations from baseline. Naltrexone would inhibit comparisons in reinforcement learning, not some absolute effect or confusion. Thus first minutes of trading experience is important in decision making. In our experiment, in the first 3–4 periods of trading (about 4.5–6 min total) in both conditions, prices and share turnovers are similar (see Table 3). Thus traders in both conditions start with similar expectations and strategies. In the subsequent trading periods both prices and turnover start to become significantly different across treatments. In these initial periods traders are starting to learn the characteristics of the trading environment, price movements, transactions, rewards in terms of capital gains and dividends, and trading strategies. According to reinforcement learning mechanism, there is continuous revising of decisions throughout the experiment, based on the analysis of prior prediction errors. After each trading period subjects revise their expectations about future period prices (Akiyama, Hanaki and Ishikawa [2013]), which is part of the learning from transaction to transaction and period to period.

Table 3. Initial 5 period comparisons in round 1, across P and N sessions.

Test	Turnover per Period	Price per Period
Wilcoxon/Mann-Whitney Rank-Sum Tests		
Period 1 p	0.186	0.608
Period 2 p	0.092	0.826
Period 3 p	0.163	0.092
Period 4 p	0.067	0.092
Period 5 p	0.046*	0.023*

There were no differences in prices and turnovers in the initial four periods of trading across treatments. The significant differences emerge in period 5 (at 5% significance level). These test results to a degree rule out differences in confusion level about fundamental values across the conditions.

*indicates significance at 5% (two tailed).

The higher price peaks and slower convergence to fundamental prices in Naltrexone suggests (but does not prove definitively) that Naltrexone inhibited learning. The Naltrexone condition's eventual convergence to fundamental prices shows that Naltrexone did not extinguish learning, it just slowed it. That's all we need in order to use a lack of learning neurologically as a contributor to bubbles.

Recent studies have emphasized the role of confusion about fundamental value (Kirchler, Huber and Stöckl [2012]). We examined our data for this possibility. We compared mean prices across treatments in initial five periods of R1. There is no difference in mean prices across treatments in initial two periods, marginal difference appears in periods 3 and 4, and difference becomes significant in period 5 (see Table 3). Thus, if initial prices are similar, most subjects across treatments have similar expectations about the fundamental values, which rules out the role of confusion level regarding fundamental values. We also tested period 1 price differences with linear regression analysis of pooled price data of all periods of trading in all sessions. The N and P session price dummies in period 1 have similar coefficients ($p = 0.64$, Wald F).

Because Naltrexone may have affected more than just learning, we collected data on participants' overconfidence, possible confusion, and understanding of trading rules. These were assessed after each 12 period trading round ended. There was no difference in any of these measures across treatments (overconfidence: R1 $p = 0.605$, R2 $p = 0.508$, R3 $p = 0.270$; understanding: R1 $p = 0.379$, R2 $p = 0.712$, R3 $p = 0.769$; confusion: R1 $p = 0.510$, R2 $p = 0.942$, R3 $p = 0.768$; two-tailed MWU). Within treatments participants did improve their understanding across rounds and showed reduced confusion regarding trading strategies between R1 and 2 (understanding: P session $M = 3.32$ (R1), 2.61 (R2), $p < 0.001$; N session $M = 3.95$ (R1), 2.53 (R2), $p < 0.001$; confusion: P session $M = 3.29$ (R1), 2.56

(R2), $p = 0.006$; N session $M = 3.75$ (R1), 2.73 (R2), $p < 0.001$; reverse 7-point scale, two-tailed paired t test). Overconfidence did not change between R1 and R2, or R2 and R3 (R1-2 P: $p = 0.58$; N: $p = 0.74$; R2-3 P: $p = 0.89$; N: $p = 0.87$). Consistent with the role of experience, diminished understanding of trading rules ($r = 0.58$, $p < 0.001$) and greater confusion ($r = 0.65$, $p < 0.001$) were associated with higher amplitude bubbles.

Earnings did not vary across conditions (P = \$26.28, N = \$25.88; $p = 0.85$). We tested if women and men earned different amounts during trading by producing ranks of earnings in R1 and R3. Men earned more than women both in P and N treatments (highest earnings = 1; women: $M = 8.56$, men: $M = 6.36$, $p < 0.001$; two-tailed t test). One possible reason for the earnings difference is that those who were less emotionally labile, assessed using the Affective Intensity Measure (Larsen, Diener and Emmons [1986]), earned less ($r = 0.319$, $p < 0.001$; χ^2 test). Women tended to be more emotionally reactive (inverse scale, female $M = 68.5$, male $M = 77.5$, $p < 0.001$; two-tailed t test). The proportion of women in a session did not affect the bubble size and was similar across P and N sessions.

We also tested several other factors that could have been related to bubbles. The spread between average buy and sell offers was larger for the N sessions (N = 161.9, P = 55.3; $p = 0.02$) round to round, this measure was highly variable and did not correlate with measures of bubbles or turnover. Bubbles were also unrelated to

excess demand for the asset, as this did not vary across treatments (excess demand P: $M = -4.95$, N: $M = -3.33$, $p = 0.81$).

Low turnover bubbles, as we report here, have been observed in experiments by Smith, Suchanek and Williams [1988], in a market with experienced, high-earning traders. Experimental asset markets generally have turnover declines after each successive round of trading as traders gain experience. We found such a volume reduction in N sessions, but not in the P sessions. Debt markets have also been found to exhibit low turnover bubbles (Hong and Sraer [2011]). Both, too low or too high turnover may be associated with bubbles when traders have beliefs that are out of line with fundamental values (Camerer [1992]). In our data, after price rises during the first three periods in both P and N sessions turnover drops. In the N sessions, average prices more than double in first three periods and more than triple in value in first six periods and then remain high. At such high prices, there can be fewer buyers, and thus fewer transactions.

Because traders cannot borrow, they are liquidity constrained producing a negative relationship between average price and turnover in high bubble rounds. A way to measure the price-volume interaction is to measure the total value of transactions (TRANS) in each period. TRANS is the product of the average price and turnover, and we compared these across conditions. No difference was found for the first 24 periods of trading, or for all 36 periods (24 periods: P session $M = 43.35$, N session

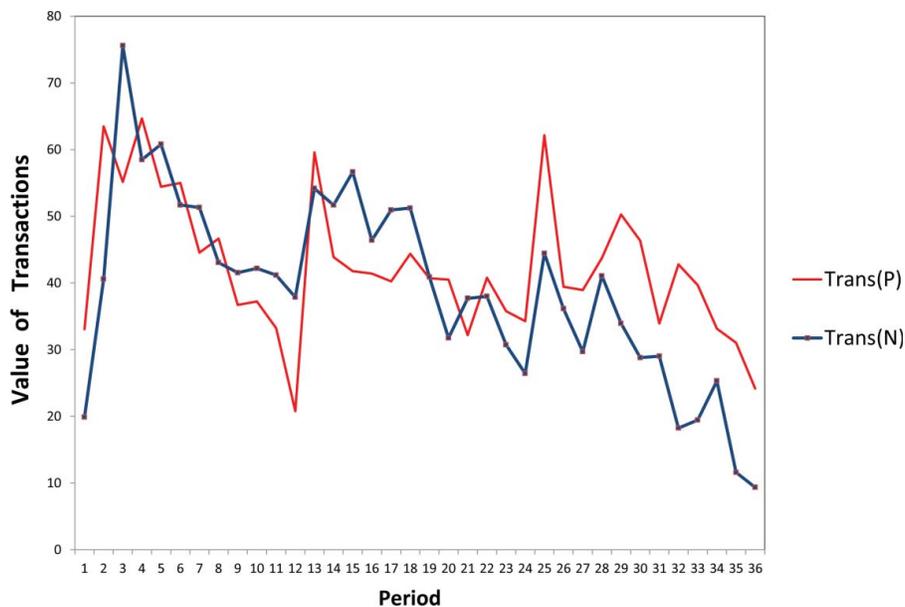


Figure 2. The total value of transactions in P and N sessions (Prices \times Turnover). The line with markers represents transactions values for each period in N sessions, and the line without markers the values for P sessions. A paired observations test provides no statistical difference between these two series (first 24 periods: P session $M = 43.35$, N session $M = 45.03$, $p = 0.42$; all 36 periods: P session $M = 42.40$, N session $M = 39.11$, $p = 0.10$; two-tailed t test).

$M = 45.03$; $p = 0.42$; 36 periods: P session $M = 42.40$, N session $M = 39.11$, $p = 0.10$; two-tailed paired t test; see Figure 2).

We examined if Naltrexone affected groups of traders' comprehension of the trading rules and the trading environment. Differences in trader's beliefs are essential to generate trades (Varian [1989]), while judgment errors may lead to price bubbles and excessively low or high turnover (Camerer [1992]). We measured heterogeneity of judgment using the standard deviations of after-round surveys of confusion, overconfidence and understanding. N sessions produced lower heterogeneity in all three measures compared to P sessions (understanding: R1 $p = 0.034$, R2 $p = 0.048$; confusion: R1 $p = 0.023$; overconfidence: R1 $p = 0.067$; two-tailed MWU). Overall, N sessions had lower turnover, fewer differences in judgment about trades, and higher price bubbles. Naltrexone's reduction in learning along with increased homogeneity of traders' judgments suggests there were fewer traders who disagreed with the high valuation of shares. As a result, the volume of trading appears to have been too low to move prices toward fundamental values. Our study did not focus on belief formation, but our evidence suggests the study of the relationship among experience, learning, and belief formation could be a fertile area for future research.

Conclusions

We have provided evidence that inhibiting reinforcement learning ability in the brain using Naltrexone produced larger bubbles in a laboratory asset trading market. This provides evidence that asset bubbles have a specific neural basis linked to reinforcement learning system. In order to rule out other effects of the treatment intervention, we demonstrated that Naltrexone did not affect participants' understanding of the trading rules, induce confusion, change earnings, affect confidence, alter initial trading prices or turnover, or change total value of transactions.

The key implication of our study is that insufficient learning through experience or training in financial markets is a source of asset bubbles. Indeed, younger money managers tend to do more trend chasing than do older ones (Greenwood and Nagel [2009]). Financial market professionals receive training before trading, though much of it is paper trading that may not make gains and losses sufficiently salient to result in memories of choices made and not made and how choices affected performance. Experience that impacts a trainee's earnings would be one way to make learning more salient neurologically.

Other assets, such as houses, are subject to bubbles but are primarily traded by nonprofessionals. Nonprofessionals may never have enough experience to remove the tendency for bubbles in these markets. Indeed, we found that those who are more emotionally reactive make less money while trading, an effect that may occur more commonly when people sell their homes. This suggests that one's emotional responses, as well as learning, play a role in bubble formation. As with professional traders, a reading of history may be insufficient to potentiate the level of learning that would reduce or eliminate bubbles. Our findings in support of neural basis of bubbles represented by reinforcement learning system suggest not only that those who cannot remember the past are condemned to repeat it but also that more meaningful trading experience with asset price booms and contractions is necessary to reduce the frequency of asset market bubbles.

Note

1. We think that existing bubble measures require further study. We do not think that there is consensus on these measures in the literature. Often authors do not elaborate how they selected the measures they report, and there is wide variation of measures used. Stöckl, Huber and Kirchler [2010] article is a good step in this direction, but more needs to be done in this area.

ORCID

Levan Efremidze  <http://orcid.org/0000-0001-6407-6985>

References

- Akiyama, E., N. Hanaki, and R. Ishikawa. "It is Not Just Confusion! Strategic Uncertainty in an Experimental Asset Market." Working Paper (2013).
- Allen, F. "Modeling Financial Instability." *National Institute Economic Review*, 192, (2005), pp. 57–67.
- Allen, F., and D. Gale. "Asset Price Bubbles and Monetary Policy." *The Economic Journal*, 110, (2000), pp. 236–255.
- Barberis, N., and R. Thaler. "A Survey of Behavioral Finance." *National Bureau of Economics Research (NBER)*, Working Paper 9222 (2002).
- Benjamin, D., E. R. Grant, and L. A. Pohorecky. "Naltrexone Reverses Ethanol-Induced Dopamine Release in the Nucleus Accumbens in Awake, Freely Moving Rats." *Brain Research*, 621, (1993), pp. 137–140.
- Blanchard, O. J. "Speculative Bubbles, Crashes and Rational Expectations." *Economics Letters*, 3, (1997), pp. 387–389.
- Bollerslev, R., R. F. Engle, and D. B. Nelson. "Arch Models." In F. E. Robert, and D. McFadden (eds.), *Handbook of Econometrics* (pp. 2959–3038). Amsterdam: Elsevier, 1986.
- Bostian, A. J., J. Goeree, and C. A. Holt. "Price Bubbles in Asset Market Experiments with a Flat Fundamental Value."

- Prepared for the *Experimental Finance Conference*, Federal Reserve Bank of Atlanta, (2005).
- Bostwick, J. M., and J. A. Bucci. "Internet Sex Addiction Treated with Naltrexone." *Mayo Clinic Proceedings*, 83, (2008), pp. 226–230.
- Caginalp, G., D. Porter, and V. L. Smith. "Momentum and Overreaction in Experimental Asset Markets." *International Journal of Industrial Organization*, 18, (2000), pp. 187–204.
- Camerer, C. "The Rationality of Prices and Volume in Experimental Markets." *Organizational Behavior and Human Decision Processes*, 51, (1992), pp. 237–272.
- Cheung, S. L., M. Hedegaard, and S. Palan. "To See is to Believe: Common Expectations in Experimental Asset Markets." *European Economic Review*, 66, (2012), pp. 84–96.
- Daniel, K., D. Hirshleifer, and S. H. Teoh. "Investor Psychology in Capital Markets: Evidence and Policy Implications." *Journal of Monetary Economics*, 49, (2002), pp. 139–209.
- Deck, C., D. Porter, and V. Smith. "Double Bubbles in Assets Markets with Multiple Generations." *Journal of Behavioral Finance*, 15, (2014), pp. 79–88.
- Dufwenberg, M., T. Lindqvist, and E. Moore. "Bubbles and Experience: An Experiment." *American Economic Review*, 95, (2005), pp. 1731–1737.
- Dayan, P., and N. D. Daw. "Decision Theory, Reinforcement Learning, and the Brain." *Cognitive, Affective, and Behavioral Neuroscience*, 8, (2008), pp. 429–453.
- Einöther, S. J., and T. Giesbrecht. "Caffeine as an Attention Enhancer: Reviewing Existing Assumptions." *Psychopharmacology (Berl)*, 225, (2013), pp. 251–74.
- Flood, R. P., and P. M. Garber. "Market Fundamentals Versus Price-Level Bubbles: The First Tests." *Journal of Political Economy*, 88, (1980), pp. 745–70.
- Greenwood, R., and S. Nagel. "Inexperienced Investors and Bubbles." *Journal of Financial Economics*, 93, (2009), pp. 239–258.
- Haruvy, E., Y. Lahav, and C. Noussair. "Traders' Expectations in Asset Markets: Experimental Evidence." *American Economic Review*, 97, (2007), pp. 1901–1920.
- Haruvy, E., and C. N. Noussair. "The Effect of Short Selling on Bubbles and Crashes in Experimental Spot Asset Markets." *The Journal of Finance*, 61, (2006), pp. 1119–1157.
- Hiemstra, C., and J. D. Jones. "Testing for Linear and Nonlinear Granger Causality in the Stock Price-Volume Relation." *Journal of Finance*, 49, (1994), pp. 1639–1664.
- Hirshleifer, D. "Investor Psychology and Asset Pricing." *Journal of Finance*, 56, (2001), pp. 1533–1597.
- Huber, J., and M. Kirchler. "The Impact of Instructions and Procedure on Reducing Confusion and Bubbles in Experimental Asset Market." *Experimental Economics*, 15, (2012), pp. 89–105.
- Hussam, R., D. Porter, and V. Smith. "Thar She Blows: Can Bubbles Be Rekindled With Experienced Subjects?" *American Economic Review*, 98, (2008), pp. 924–937.
- Hong, H., and D. Sraer. "Quiet Bubbles." Working Paper, Princeton University (2011).
- Hyman, S. E. "Addiction: A Disease of Learning and Memory." *American Journal of Psychiatry*, 162, (2005), pp. 1414–1422.
- King, R., V. L. Smith, A. W. Williams, and M. V. Van Boening. "The Robustness of Bubbles and Crashes in Experimental Stock Markets." In R. H. Day, and P. Chen (eds.), *Nonlinear Dynamics and Evolutionary Economics*. New York: Oxford University Press, 1993.
- Kirchler, M., J. Huber, and T. Stöckl. "Thar She Bursts – Reducing Confusion Reduces Bubbles." *The American Economic Review*, 102, (2012), pp. 865–883.
- Knutson, B., and P. Bossaerts. "Neural Antecedents of Financial Decisions." *Journal of Neuroscience*, 27, (2007), pp. 8174–8177.
- Larsen, R. J., E. Diener, and R. A. Emmons. "Affect Intensity and Reactions to Daily Life Events." *Journal of Personality and Social Psychology*, 51, (1986), pp. 803–814.
- Liu, X., M. Palmatier, A. R. Caggiula, A. F. Sved, E. C. Donny, and M. Gharib. "Naltrexone Attenuation of Conditioned But Not Primary Reinforcement of Nicotine in Rats." *Psychopharmacology*, 202, (2009), pp. 589–598.
- Lo, A. W., H. Mamayasky, and J. Wang. "Asset Prices and Trading Volume Under Fixed Transactions Costs." *Journal of Political Economy*, 112, (2004), pp. 1054–1090.
- Lo, A. W., and D. V. Repin. "The Psychophysiology of Real-Time Financial Risk Processing." *Journal of Cognitive Neuroscience*, 14, (2002), pp. 323–339.
- Montague, R. "Neuroeconomics: A View From Neuroscience." *Functional Neurology*, 22, (2007), pp. 219–234.
- Nehlig, A. "Is Caffeine a Cognitive Enhancer?" *Journal of Alzheimer's Disease*, 20, (2010), pp. S85–94.
- Noussair, C., and S. Tucker. "Futures Markets and Bubbles Formation in Experimental Asset Markets." *Pacific Economic Review*, 11, (2006), pp. 167–84.
- Noussair, C., and S. Tucker. "Cash Inflows and Bubbles in Asset Markets with Constant Fundamental Values." Working Paper, University of Waikato (2014).
- Okina, K., M. Shirakawa, and S. Shiratsuka. "The Asset Price Bubble and Monetary Policy: Japan's Experience in the Late 1980s and the Lessons." *Monetary and Economic Studies*, 19, (2001), pp. 395–450.
- Park, J. W., and P. J. Zak. "Neuroeconomics Studies." *Analyse und Kritik*, 29, (2007), pp. 47–59.
- Porter, D. P., and V. L. Smith. "Futures Contracting and Dividend Uncertainty in Experimental Asset Markets." *Journal of Business*, 68, (1995), pp. 509–41.
- Ramsey, J. D., S. J. Hanson, C. Hanson, Y. O. Halchenko, R. A. Poldrack, and C. Glymour. "Six Problems for Causal Inference From fMRI." *Neuroimage*, 49, (2010), pp. 1545–1558.
- Ramsey, N. F., M. A. Gerrits, and J. M. Van Ree. "Naltrexone Affects Cocaine Self-Administration in Naïve Rats Through the Ventral Tegmental Area Rather Than Dopaminergic Target Regions." *European Journal of Neuropsychopharmacology*, 9, (1999), pp. 93–99.
- Santos, M. S., and M. Woodford. "Rational Asset Pricing Bubbles." *Econometrica*, 65, (1997), pp. 19–57.
- Sapra, S., L. E. Beavin, and P. J. Zak. "A Combination of Dopamine Genes Predicts Success by Professional Wall Street Traders." *Public Library of Science ONE*, 7, (2012), e30844. doi:10.1371/journal.pone.0030844.
- Scheinman, J. A., and W. Xiong. "Overconfidence and Speculative Bubbles." *Journal of Political Economy*, 111, (2003), pp. 1183–1219.
- Schultz, W., P. Dayan, and P. R. Montague. "A Neural Substrate of Prediction and Reward." *Science*, 275, (1997), pp. 1593–1599.
- Shiller, R. *Irrational Exuberance*, 3rd Edition. Princeton: Princeton University Press, 2015.
- Smith, A. "Effects of Caffeine on Human Behavior." *Food Chemical Toxicology*, 40, (2002), pp. 1243–1255.

- Smith, A., T. Lohrenz, J. King, R. Montague, and C. Camerer. "Irrational Exuberance and Neural Crash Warning Signals During Endogenous Experimental Market Bubbles." *Proceeding of National Academy of Sciences*, 111, (2014), pp. 10503–10508.
- Smith, V. L., G. Suchanek, and A. Williams. "Bubbles, Crashes, and Endogenous Expectations in Experimental Spot Asset Markets." *Econometrica*, 56, (1988), pp. 1119–1151.
- Stöckl, T., J. Huber, and M. Kirchler. "Bubble Measures in Experimental Asset Markets." *Experimental Economics*, 13, (2010), pp. 284–298.
- Stöckl, T., J. Huber, and M. Kirchler. "Multi-Period Experimental Asset Markets with Distinct Fundamental Value Regimes." *Experimental Economics*, 18, (2014), pp. 314–334.
- Tirole, J. "On the Possibility of Speculation Under Rational Expectations." *Econometrica*, 50, (1982), pp. 1163–1181.
- Varian, H. R. "Differences of Opinion in Financial Markets." In C. C. Stone (ed.), *Financial Risk: Theory, Evidence and Implications* (pp. 3–40). Norton: Kluwer Academic Publishers, 1989.
- Vercoe, M., and P. J. Zak. "Inductive Modeling Using Causal Studies in Neuroeconomics: Brains on Drugs." *Journal of Economic Methodology*, 17, (2010), pp. 123–137.
- Vul, E., C. Harris, P. Winkielman, and H. Pashler. "Puzzlingly High Correlations in fMRI Studies of Emotion, Personality, and Social Cognition." *Perspectives on Psychological Science*, 4, (2009), pp. 274–290.
- Zak, P. J. "Neuroeconomics." *Philosophical Transactions of the Royal Society B (Biology)*, 359, (2004), pp. 1737–1748.