Efficiency and Adaptive Expectations in Experimental Asset and Digital Option Markets

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ABSTRACT

In asset markets, extraordinary price run-ups (bubbles) followed by crashes back to levels closer to fundamental values have been shown to adversely affect the real economy, leading to inefficient resource allocation and underinvestment. Conversely, derivative markets contribute to price discovery and lead to informationally more efficient prices in the market for the underlying asset. We combine these observations and test experimentally whether digital options – a type of derivative that has recently been introduced to a wider audience via online prediction markets – can reduce price bubbles in a laboratory setting. We find that subjects do not use the derivative market to improve their forecasts of future asset prices and formulate a hypothesis to explain this result.

JEL classification: G01, D01, D02

Working Paper, Version 2008-12-19

Digital Options and Efficiency in Experimental Asset Markets

ABSTRACT

In asset markets, extraordinary price run-ups (bubbles) followed by crashes back to levels closer to fundamental values have been shown to adversely affect the real economy, leading to inefficient resource allocation and underinvestment. Conversely, derivative markets contribute to price discovery and lead to informationally more efficient prices in the market for the underlying asset. We combine these observations and test experimentally whether digital options – a type of derivative that has recently been introduced to a wider audience via online prediction markets – can reduce price bubbles in a laboratory setting. We find that subjects do not use the derivative market to improve their forecasts of future asset prices and formulate a hypothesis to explain this result.

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THE RESEARCH QUESTION UNDERLYING THIS ARTICLE is motivated by three loosely related topics in financial economics. The first of them is the propensity of market prices to sometimes exhibit extraordinary run-ups (bubbles) followed by crashes back to levels closer to fundamental values. This phenomenon has been documented as early as after the disintegration of the tulip price bubble in the Netherlands in 1637 or the plunge in stock prices of the South Sea Company in the UK in 1720. In the last century, the Great Depression in the 1930s clearly demonstrated the danger that spillover effects from price bubbles in financial markets pose for the underlying real economy. The current financial crisis following the crash of a price bubble in U.S. real estate prices in 2007 forms another example that will be subject to intense analysis in the coming years.

Bubble-and-crash patterns in financial market prices are widely considered harmful to economic activity in general, since they cause a misallocation of available resources to non-optimal uses. As a case in point, Gan (2007) documents how the adverse liquidity shock experienced by Japanese banks in the early 1990s led to reduced lending, which in turn had significant repercussions on both the real investments and the performance of capital-deprived Japanese firms. His study showcases an indirect transmission channel from asset market bubbles to the real economy, underlining the possible efficiency gains to be had from a better understanding of the bubble phenomenon.

The second strand of research impacting on our work saw its beginnings in the 1970s. Cox (1976) was one of the earliest articles to model the link between futures trading and the information processing taking place in the formation of spot market prices. Since then, an extensive branch of literature has been devoted to the connection between the trading of forwards, futures and options and its impact on the informational efficiency of the market price of the underlying asset. Both theoretical and empirical studies have shown that derivatives markets generally process information earlier and faster than spot markets and that the creation of a derivatives market to accompany a spot market usually leads to higher price efficiency in the latter.[1] One explanation for this effect is proposed by Figlewski and Webb (1993), who reason that options give traders who cannot or will not engage in short sales due to e.g. transaction costs, an opportunity to sell short indirectly.

The final component motivating our research is the emergence of a new type of online marketplace permitting the trading in digital options. Prediction markets and online betting sites like binarybet.com, intrade.com, mybet.com and redmonitor.com are relatively new ventures which allow investors to trade cash-or-nothing (digital) options on financial market prices. A cash-or-nothing option returns a fixed cash amount in the case that it expires in the money and nothing if it expires out of the money. These options are sometimes referred to as “binary bets” in real-world markets and are being marketed as being easier to understand than conventional bets (cp. Oliver (2007)). The sites mentioned above have in common that there are low barriers to entry and that trades can be initiated with relatively small investment volumes and transaction costs.

Our article brings together the above three pieces of motivation. It aims at providing evidence regarding the question of whether the adverse effects of price bubbles in financial markets can be reduced if markets are provided with the forward-looking price information from digital option markets. We attempt to uncover the effects of giving traders an opportunity to trade digital options under the controlled conditions of a laboratory experiment. The design we employ is a modification of the experimental double auction asset market introduced in Smith et al. (1988), hereafter referred to as SSW.

The rest of this article is structured as follows: Section I discusses some background issues and develops our hypotheses. Section II then introduces our experimental design. Section III reports the results of our experiments and provides a brief comparison with previous results from the literature. Section IV concludes the paper and proposes several new research questions.

I. Background and Hypotheses

Our experiment is modeled after the seminal contribution of SSW. They find that although the possible dividend draws in their laboratory markets are common information and all traders have all the information required to derive the fundamental value of the stock in every period, there is a persistent pattern across inexperienced subjects: The stock price starts out below its fundamental value in period 1. Over the course of the experiment, the stock price then rises above its fundamental value,

[1] O’Hara (1995) is one of the best sources for theoretical work on this topic. In an empirical study, Easley et al. (1998) show that option volumes lead stock price changes and carry information about future stock price changes. Similarly, Jayaraman et al. (2001) find that option markets lead equity markets in terms of volume. Chakravarty et al. (2004) employ an approach pioneered by Hasbrouck (1995) to measure that between a stock and an option market, on average between 17 and 18 percent of price discovery occurs in the option market.

creating a bubble. During the final periods, the price crashes down to levels close to its fundamental (intrinsic dividend) value.

These results have in the past 20 years been replicated numerous times, with a wide array of variations, and have been found to be remarkably robust.[2] The only variable that has been observed to reliably lead to a disappearance of the observed bubble is experience. Subjects who have played the same experiment once or twice before produce a price series that follows the fundamental price series significantly more closely, with bubbles usually vanishing entirely by the second repetition.

While not leading to a disappearance of bubbles, the addition of a derivatives market to the spot asset market has been found to cause a decline in measures of the extent of price bubbles. Forsythe et al. (1982, 1984) use a somewhat different design than that of SSW, but find that futures markets do accelerate convergence and that in the absence of futures markets, even experienced traders have problems overcoming the existing coordination problems. Friedman et al. (1983, 1984) conduct similar experiments and confirm the higher informational efficiency of asset market prices in the presence of a futures market. Porter and Smith (1995), hereafter referred to as PS, introduce a futures market to the SSW design, while staying true to the original institution in all other respects. They report a reduction of the amplitude of the observed price bubble in their spot-and-futures treatment relative to the spot-only treatment. In a different approach, De Jong et al. (2006) modify the SSW baseline experiments both by adding an option market to the spot market and by introducing three market makers and an insider. They find that price efficiency in the asset market is higher and the asset's price volatility lower when the intrinsic value of the option is positive. They also note more generally that the presence of any option (i.e. even if its intrinsic value is zero) improves market efficiency.

The hypothesis we wished to explore with our experiment was that the constant visibility of the expected stock price in a future period (as revealed in a digital option market) leads to a reduction in the extent of the observed bubble. Our first design closely resembles the PS futures market discussed above.

[2] Modifications of the original SSW design were made with regard to many dimensions: Variations in dividends featured certain dividends (Porter and Smith (1995)), a symmetric discrete dividend distribution with unequal probabilities over outcomes (Van Boening et al. (1993)), variations in the structure of dividend payments over time (Smith et al. (2000), Caginalp et al. (2001), Oechssler et al. (2007)), a dividend payment date beyond subjects' investment horizon (Hirota and Sunder (2007)), a dividend regime that induced a non-monotonic fundamental value process (Noussair and Powell (2008)), and an expected dividend of zero, yielding a constant expected asset value (Caginalp et al. (2001), Noussair et al. (2001)). Some studies varied the reward function by employing play money instead of real money payouts (Smith (1962), Forsythe et al. (1982)), introducing trading commissions and transaction costs (Friedman et al. (1983) and (1984), King et al. (1993)), or deviating from the practice of payouts being linearly related to the wealth amassed in the experiment (Ang and Schwarz (1992), James and Isaac (2000), Luckner and Weinhardt (2007)). Another class of variations targeted the ability of subjects to short-sell (King et al. (1993), Sunder (1995), Ackert et al. (2001), Ackert et al. (2006), Haruvy and Noussair (2006)). An important variation was preventing speculation by assigning subjects the role of either buyer or seller (Lei et al. (2001)). Other modifications concerned the transaction mechanism (Van Boening et al. (1993)), multiple assets (Fisher and Kelly (2000)), uninformative announcements (Corgnet et al. (2007)), non-stationary repetition (Hussam et al. (2008)), and computer simulation (Gode and Sunder (1993)).

Building on these results and observations, we conjecture that the opportunity of trading in a digital option market reduces the frequency and extent of bubble observations in SSW-type markets, as quantified by three standard bubble measures:

Hypothesis 1: Trading in a digital option market in addition to a spot market reduces the *amplitude* of observed bubbles relative to the SSW baseline design.

Hypothesis 2: Trading in a digital option market in addition to a spot market reduces the *duration* of observed bubbles relative to the SSW baseline design.

Hypothesis 3: Trading in a digital option market in addition to a spot market reduces the *turnover* of observed bubbles relative to the SSW baseline design.

II. Experimental Design

A. Stock and Option Markets

Subjects in the experiment can trade over 15 periods in a market for an asset (referred to as a stock) and in a second market for digital options written on the asset. In keeping with the original SSW design, the stock market employs the continuous double auction mechanism. At the end of each period, each share of stock pays a random dividend after the market close. Dividends are drawn from a discrete uniform distribution with four equiprobable dividend values (0, 8, 28 or 60 Euro cents). The stock has no terminal value, causing its fundamental value to decline by the expected dividend (24 cents) in each period.

In the digital option market, subjects can specify a price they expect the future stock price to exceed or fall short of (long or short position) and also specify the amount of their wealth they want to invest in this option. We have two different treatments, which differ with regard to the maturity of the option. In the digital options treatment DO8, options can be traded from periods 1 to 8; all options expire at the end of period 8 and are judged using the stock price at the end of period 8. Starting from period 9, the option market is closed. In DO5/10/15, options that are created in periods 1 to 5 expire at the end of period five, options created in periods 6 to 10 expire at the end of period 10 and options created in periods 11 to 15 expire at the end of period 15. This time structure is illustrated in Figure 1. A subject's payoff from an option at maturity is:

$$PO_{t=M,\theta} = \begin{cases} 2 \cdot SI \cdot (1-\theta) & \text{if } S_M < X \\ SI & \text{if } S_M = X \\ 2 \cdot SI \cdot \theta & \text{if } S_M > X \end{cases}$$

where $M \in \mathbb{M}^{\mathrm{DO8}} = \{8\}$ is the option's maturity date in the DO8 treatment and $M \in \mathbb{M}^{\mathrm{DO5/10/15}} = \{5{,}10{,}15\}$ in the DO5/10/15 treatment, θ equals 1 if the subject holds a call and 0 if the subject holds a put option, SI is the stake invested into the option by the subject, S_M is the stock price at maturity and X is the option's strike price. The profit from such an option then is $PO_{t=M,\theta} - SI$.[3] All prices in the experiment are quoted in Euro cents (€ 0.01). There are no transaction costs in our stock and option markets.

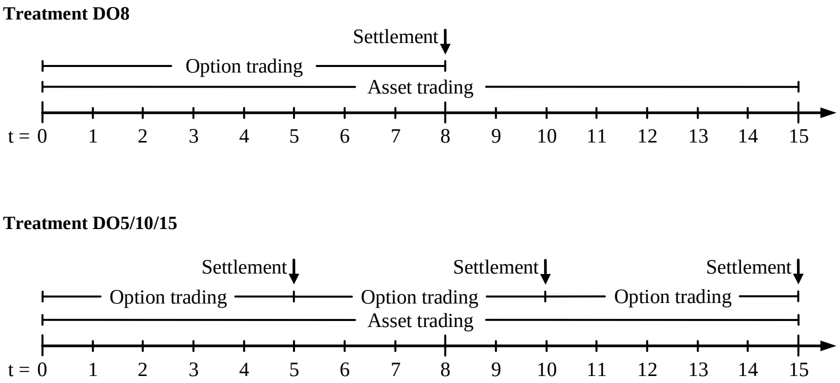


Figure 1. Time structure of spot and option trading, DO8 and DO5/10/15 treatments. Illustration of the time structure of spot and option trading in the DO8 (upper panel) and DO5/10/15 treatments. The stock trading structure is identical between treatments; option trading differs with regard to option maturity and because no option can be traded in periods 9-15 of treatment DO8.

In the digital option design, subjects can, in addition to the information about price and order direction, reveal the strength of their convictions through the amount of money they invest in their digital option quotes (e.g. "I bet 300 cents that the stock price in period eight will exceed 100"). The digital option market thus provides a richer information set than e.g. a futures market. We test whether this more direct revelation (and backing up) of expectations leads to a similar or larger reduction in bubble indicators than the PS design. Our close adherence to their setup in our treatment DO8 – in everything but the choice of derivative instrument – was deliberately chosen to ensure the comparability of our results with their conclusions and with the outcomes of other studies using a similar experimental design.

We later introduced the treatment design DO5/10/15 when we observed a structural break between the eighth and ninth period in our DO8 treatment, a point in time that coincides with the option maturity date. We gained the impression (supported by anecdotal evidence from post-round questionnaires) that prior to the end of period 8, subjects' attention with regard to the stock price was focused on the levels of their options' strike prices. In other words, approaching period 8, traders seemed to try to move their options into the money by adjusting the transaction prices they quoted and accepted in the stock market. Only once the option outcomes had been decided

[3] Since one period in the experimental market can be thought of as corresponding to one day in a real market, no interest was paid on cash holdings, nor was it taken into account in any value calculations. This is reasonable also because one round lasts around 2 hours in real time, making virtually zero any possible real-world interest requirement founded on a time-preference argument.

did they let the fundamental dividend value reenter their stock price expectations formation process. We designed the DO5/10/15 treatment specifically to test whether more frequent option maturity dates would hasten the return to fundamental values.

B. Session Design

Table I gives an overview of the experimental sessions held. We conducted four sessions using the DO8 treatment and three sessions with the DO5/10/15 treatment. All sessions were run using z-Tree (cp. Fischbacher (2007)) and structured as follows: The subjects arrived and were seated at computers. The instructions were handed out and read by the subjects (approximately 1 hour). Special care was taken that subjects understood the evolution of the stock's fundamental value (i.e. the fact that the stock had no terminal value was stressed in the instructions and subjects received a table listing the fundamental stock value for every period). The trading institution was explained using detailed examples, and several review questions were discussed with the subjects to make sure they had understood the market structure. In the next step, the z-Tree program was started and all subjects participated in two two-period test rounds to familiarize themselves with the screen layout, interface and market mechanics (app. 0.5 hour).[4] Following the test rounds, one 15-period experiment was run (app. 1.5 hours), after which the subjects filled in a questionnaire on their screens (app. 0.25 hours), which is reprinted in Table A.1 in the appendix. This treatment was followed by a lunch break and by a second 15-period experiment (with the same treatment design, but with starting cash and stock inventories that varied for some subjects), once again followed by the subjects filling in the (same) questionnaire. After this, subjects were asked into an extra room, where they received their payment anonymously.[5]

[4] Subjects participating in the DO8 treatment could trade a digital option during period 1 of the test round, which expired at the end of period 1. In period 2, the option market was closed. Participants of the DO5/10/15 treatment could trade options in both test periods; these options expired at the end of period 1 and of period 2, respectively.

[5] Most similar studies play each round on a different day, which gives subjects time to recuperate and reflect on the task they are faced with (an exception is Haruvy et al. 2007, who play three rounds in one day). We chose not to follow this pattern mainly because we wanted to ensure that all subjects would return for the repeat rounds and that the time in which subjects could discuss the experiment would be minimized. Our observations confirmed that subjects were highly motivated to perform well in the repeat round and – having consumed lunch between the first and second rounds – did not appear to lack energy and attention.

Table I

The Sessions

Five experiments were conducted at the Karl-Franzens-University Graz, Austria and two at the Alpen-Adria University Klagenfurt, Austria. All experiments were conducted by the author as the sole experimenter. The treatments differ with regard to the option maturity dates. In DO8, option trading is possible from periods 1 to 8 with all options being settled at the end of period eight. In DO5/10/15 there is option trading from period 1 to 5, from 6 to 10 and from 11 to 15, with options being settled at the end of the last trading period in each interval.

Experiment	Treatment	Date	Location	Number of subjects
1	DO8	11/10/07	Graz	12
2	DO8	12/01/07	Graz	12
3	DO8	12/17/07	Graz	11
4	DO8	12/18/07	Graz	12
5	DO5/10/15	12/19/07	Graz	13
6	DO5/10/15	02/13/08	Klagenfurt	12
7	DO5/10/15	02/14/08	Klagenfurt	14

The payout consisted of the initial wealth (including a loan of € 10), plus any proceeds from stock sales, minus any expenditures for stock purchases, plus dividends received from shares held at the end of each period, minus all investments in options, plus all proceeds from options at their maturity date, minus the loan of € 10 (in each session), plus a € 3 attendance fee (payable once per experiment). A subject's payout function from the experiment thus was (all values expressed in Euro):

$$P = \max\left[0, \sum_{s=1}^{2}\left\{W_{s,t=0} + \sum_{t=1}^{15}\left(ST_{s,t=0} + d_{s,t}\cdot x_{s,t} - SI_{s,t} + PO_{t=M}^{o\in\mathbb{O}_{s,t=M}}\right) - 10\right\} + 3\right],$$

where s is the experimental session, t is the period within a session, $W_{s,t=0}$ is the subject's initial wealth at the beginning of the first period of session s (including the loan), $ST_{s,t=0}$ is the sum of all proceeds from stock sales minus the total cost for all stock purchases in period t of session s, $d_{s,t}$ is the dividend per share, $x_{s,t}$ designates the number of shares held by the subject at the end of period t, $SI_{s,t}$ is the investment in options entered by the subject in period t of session s, $\mathbb{O}_{s,t=M}$ is the set of options with maturity M in session s held by the subject and $PO_{t=M}^{o\in\mathbb{O}_{s,t=M}}$ is the sum of the payoffs from all options in the set $\mathbb{O}_{s,t=M}$ when t equals the option's maturity M, for all members of the set $\mathbb{M}$ (and zero when t is not an option maturity date). The maximum term in the payout function guarantees that subjects cannot make losses exceeding the attendance fee.[6]

[6] Of the 86 subjects, 5 would have attained a negative payout value (including the attendance fee) and received a payout of zero.

The subjects were students, mainly recruited in bachelor and master courses in banking, finance and economics. Of the subjects participating in the DO8 (DO5/10/15) treatment, 34% (12.8%) had previously participated in laboratory experiments, and 25.5% (15.4%) claimed to have participated in previous experiments involving the trading of financial securities in a market setting, though to the best of our knowledge nobody had previously participated in an SSW-type experiment.

Table II

Initial Trader Portfolios

The table lists the three different initial endowments of traders. Low-cash portfolios carry a high number of shares and vice versa. Each portfolio is complimented by a € 10 loan, repayable at the end of the experiment. All portfolios have equal fundamental value.

Portfolio type	Initial stock (number of shares)	Initial cash (€)	Loan (€)	Expected Earnings (€)
A	1	9.45	10.00	13.05
B	2	5.85	10.00	13.05
C	3	2.25	10.00	13.05

For the test rounds, subjects received endowments of cash from a discrete, integer-only uniform distribution over the interval [225, 945] (in cents) and of stock from the same distribution over [1, 3] (in units). For the experiments, each trader received one of three starting portfolios of cash and stock, each of which carried an expected value of € 13.05. These portfolios are shown in Table II and are the same as the endowments in the futures treatment of PS (Table 2, p. 517). Endowments were reinitialized after each session, following the above distributions in case of the test rounds and following a mapping scheme that is reprinted in Table C.1 in the appendix for the real experiments. The two test rounds did not count towards the payout. The expected earnings per subject participating in an experiment comprising two sessions were € 29.10 (including the show-up fee of € 3). The period length in the test rounds varied between five and six minutes, the period length in the experiments between four and five.[7]

The subjects' information sets included the number and identity of the subjects, the current best bid and ask in the stock market, their own outstanding stock quotes, and all outstanding option quotes (composed of the winning condition and the amount invested by the offerer). In addition to this information, their screens displayed their current stock and cash holdings, the period number, the time remaining until the end of the period, and the last stock and option transaction price. Each trader also saw a table listing her past stock transactions (period and price) as well as the options she currently held (winning condition and possible payoff). Traders could submit and cancel quotes in the stock and option markets at any time, subject to no-short-sale and no-margin-buying constraints (excluding the loan of € 10). Option quotes that

[7] Similar to PS, we increased the trading time in periods where both the derivative and the spot market were open.

had found a counterparty and had thus been transformed into a binding contract were uncancelable.[8]

In the stock market, subjects could enter new bids (asks) if they improved the current highest (lowest) outstanding offer to buy (sell). They could also buy (sell) a share at the prevailing ask (bid) price by clicking a button labeled "Buy at market price" ("Sell at market price"). In the option market, subjects could submit new option quotes, with their investment bounded from above by their cash holdings. Immediately upon entry, new quotes were checked against existing quotes to determine whether there existed any conflicts. If the new quote conflicted with an outstanding old quote, they were matched and converted into options contracts. The matching was processed to favor the trader posting the newest quote. In other words, quotes that bet on prices lower (higher) than the specified strike price were matched against the conflicting quote with the highest (lowest) price first. Each stock transaction led to the share of stock being transferred from the seller's to the buyer's inventory and cash matching the transaction price being transferred from buyer to seller. In an option transaction, nothing happened if the new quote did not conflict with any outstanding quotes. If there was a conflict, a cash amount corresponding to each counterparty's investment in the newly-formed option was deducted from their inventory. Only when the options reached maturity was their outcome decided and the sum of the investments paid to the subject holding the option that was in the money. In the case where the option matured at the money, each counterparty's investment was returned.[9]

III. Experimental Results

We report the results of our experiments in Table III at the end of this section. To offer comparability with previous work, we calculate three of the most common measures of market efficiency and bubble extent that have in the past been reported in the literature. In addition to these analytical measures, every subject answered a questionnaire at the end of each 15-period market. A translation of this questionnaire and some summary statistics of our subjects' replies are printed in Appendix A.

A. Measures of Bubble Severity

A large number of measures documenting bubble extent and severity can be found in the literature (e.g. Ackert et al. (2006), King (1991), King et al. (1993), Noussair et al. (2006), PS, SSW, Van Boening et al. (1993)). In the interest of comparability, we calculate three relevant and frequently reported measures both for our experimental results and for two earlier studies employing treatment designs based on

[8] See Crowley and Sade (2004) for a study analyzing the effect of permitting the cancellation of orders on trading volume and prices in a double auction environment.

[9] This happened in 0.85% of all cases. More specifically, 0.74% of all option contracts in the DO8 treatment and 1.02% of the DO5/10/15 treatment options were found to be at the money at maturity.

SSW.[10] A higher value of any variable is associated with a bubble of larger magnitude. The first of the three measures reported in Table III is the Amplitude of a bubble, which gives an indication of the magnitude of peak-to-trough deviations of market prices from the fundamental value. *Amplitude* $= \max[(P_t - f_t) / f_1] - \min[(P_t - f_t) / f_1]$, where P_t equals the mean transaction price in period t and f_t is the fundamental value in period t. Second, the *Duration* measures the temporal length of a bubble. *Duration* $= \max(m: P_t - f_t < P_{t+1} - f_{t+1} < \ldots < P_{t+m} - f_{t+m})$. This formula defines as the duration of a bubble the longest uninterrupted interval during which the deviation of mean period prices from period fundamental values increases. The third measure, *Turnover*, documents the trading volume in the stock market. It is defined as *Turnover* $= (\Sigma_t q_t) / q$, where q_t is the number of stock transactions in period t, and q (sometimes referred to as TSU, or Total Stock of Units) is the total number of shares in the experimental market. Note that in a market with common knowledge about the rationality of all traders, risk-aversion would be the only factor motivating (limited) trading.[11] For this reason, high *Turnover* can be considered indicative of a price bubble.

Table III

Bubble Measure Results

This table compares bubble measures reported in the literature for experimental asset markets. Our own results are printed in bold at the bottom of each block. All numbers reported in columns 2-4 are means over all markets conducted with the stated treatment and level of experience. The last column lists the number of rounds the reported measures are the mean of, for each level of experience. The duration measure cannot be calculated for all studies due to a lack of reported data.

Measure	Experience		
Article / Treatment	None	Once	n
Amplitude			
Ackert and Church (2001) – Baseline	1.07	0.52	3;2
—Non-business	1.21	0.67	3;2
Porter and Smith (1995) – Baseline	1.53	0.86	10;8
—Futures	0.92	0.60	3;2
Smith et al. (2000) – Baseline	1.39	0.93	6;3
Van Boening et al. (1993) – Call auction	1.61	1.18	2;2
This article – DO8	**1.24**	**0.93**	**4;4**
—DO5/10/15	**1.57**	**1.02**	**3;3**

[10] More bubble measures and transaction-level data are available upon request.

[11] In the case of common knowledge about rationality, shares of the risky stock would be transferred from subjects with a higher risk-aversion to subjects with lower risk-aversion. Once a Pareto optimal allocation has been attained, trading would cease.

Duration			
Ackert and Church (2001) – Baseline	9.33	2.50	3;2
—Non-business	9.00	5.00	3;2
Porter and Smith (1995) – Baseline	10.15	4.75	10;8
—Futures	10.00	5.50	3;2
This article – DO8	**11.00**	**6.75**	**4;4**
—DO5/10/15	**11.00**	**7.00**	**3;3**
Turnover			
Ackert and Church (2001) – Baseline	2.45	1.05	3;2
—Non-business	2.02	0.85	3;2
Porter and Smith (1995) – Baseline	5.49	2.98	10;8
—Futures	6.85	2.63	3;2
Smith et al. (2000) – Baseline	5.18	3.20	6;3
Van Boening et al. (1993) – Call auction	3.08	1.68	2;2
This article - DO8	**6.31**	**4.22**	**4;4**
—DO5/10/15	**5.68**	**4.79**	**3;3**

Table III lists the results for these bubble measures for four treatments from previous studies in the literature and for the two treatments presented in the present article. The *Amplitude* measure demonstrates that the digital option treatments do not produce better results than the SSW baseline design or than experiments with non-business-major student subjects (designated "Non-business" in Table III). The only design which consistently yields higher-altitude bubbles is a treatment from Van Boening et al. (1993) using call auctions. The PS futures treatment, conversely, is associated with a considerably smaller bubble Amplitude. The two measures of *Duration* and *Turnover* paint a similar picture. Taken together, our three hypotheses that trading in a digital option market reduces the extent of bubbles can be clearly rejected. The reason for this failure of a non-redundant market to lead to an increase in informational efficiency has its roots in the same mechanism that leads to bubbles in the first place: (Some) subjects do not condition on fundamental value.

B. *The Hypothesis of Observation-Based Belief Adaptation*

Figure 2 plots the price deviations of mean transaction prices from the fundamental prices induced by the expected subsequent dividend payments, for each treatment and period.[12] All our price processes follow paths similar to, but certainly no more efficient than, those reported for the baseline series in the literature. Over the course

[12] We used feedback from subjects during the experiment and from the questionnaires to identify and remove outliers that could be clearly identified to have been caused by errors in data entry. Specifically, we removed one outlier from period 8 in the first session of experiment 4, one from the first (period 9) and two from the second session (both period 15) of the fifth experiment and one each from the two sessions (period 7 and period 1, respectively) of the sixth experiment. This corresponds to 0.429 such outliers per session, or 0.029 per period. The results do not change materially if these outliers are retained.

of a round, prices rise from close to the dividend holding value to levels significantly exceeding this fundamental benchmark,[13] and then crash back to levels close to the stock's intrinsic value during the later periods. Experience improves (i.e. lowers) most measures of the extent of the price bubble (see Table III). While this result is well-documented in the literature, the process of how this improvement with experience comes about has not received such widespread attention. PS conclude that common information about the fundamental value of the stock is not a sufficient condition for common expectations.

Our results suggest that, due to behavioral uncertainty and irrationality, common expectations and convergence to fundamental value only come about through experience, not through logic applied to common information. We will refer to this conjecture as the *Hypothesis of Observation-Based Belief Adaptation*. Note that this hypothesis is consistent with the findings of Lei et al. (2001), who prove that bubbles are not (solely) due to subjects speculating on being able to sell a stock that they buy at a high price (relative to fundamental value) today for an even higher price in the future. Rather, they report that subjects can be shown to act irrationally in experiments where they are assigned fixed roles of either buyer or seller, since they purchase (sell) shares at prices above (below) the maximum (minimum) possible dividend value, even though they cannot reap capital gains by selling (purchasing) stock in the future.

[13] A t-test of the mean of the price deviations from fundamental value being smaller or equal to zero yields a p-value of 0.0000 overall, for both treatments, and for all levels of experience.

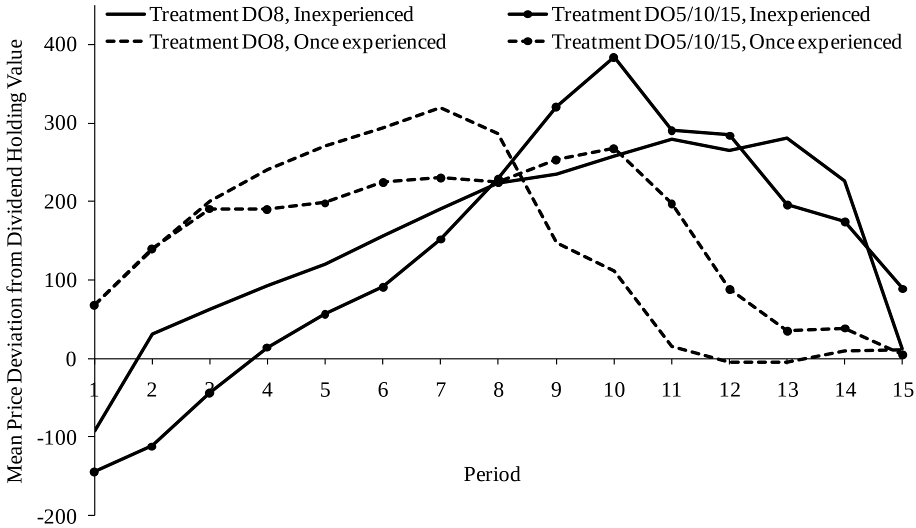


Figure 2. Mean price deviation from dividend holding value. The five plots show, for each treatment and two levels of experience, the mean over all sessions of the mean stock price per period. Inexperienced subjects have never participated in an experiment of this type and once experienced subjects are the same individuals in the second trading session. There were no periods without stock transactions.

The following observations with regard to Figure 2 show that our findings support such a mechanism of learning by observation. We find from our questionnaires and from conversations with our experimental subjects that participants in our experiment are surprised by the paths prices take during the first session (the two solid lines in Figure 2), which in all of our sessions conform closely to the typical bubble-and-crash pattern. Consistent with the Hypothesis of Observation-Based Belief Adaptation, subjects then seem to 'learn to bubble and crash' from this first session. More specifically, subjects learn that the session starts with strongly positive price developments, followed by a price downturn towards the end. In anticipating this now familiar pattern, they strengthen the pattern of large positive price changes in the early periods and hasten the subsequent return of prices to levels near fundamental value. As Figure 2 shows, the mean price paths of the once experienced treatments up to period 7 are strictly above those of the inexperienced treatments. Also, in the experienced treatments, prices are closer to dividend value than in the inexperienced treatments from period 11 onwards.

The same pattern can be observed in PS (Figure 1, p. 511), and even SSW already noted that their sessions 26 and 28x (both using the same subjects) conform to this pattern. We interpret this as evidence consistent with the Hypothesis of Observation-Based Belief Adaptation. If, by participating in the first period, subjects had improved their understanding of the market and recognized that prices at the end of the session tended towards fundamental value (an alternative hypothesis sometimes found in the literature, cp. e.g. Ackert and Church (2001), p. 18), one would assume that the crash should occur earlier – as it does – and the run-up to the bubble should be dampened – which it is not.

Finally, the Hypothesis of Observation-Based Belief Adaptation also predicts why increasing experience leads to more efficient prices. Subjects who observe the crash in the first session usually anticipate this pattern, which leads to an earlier crash in the second session. By the third session, subjects have learnt that the moment where prices start to return to fundamental values moves forward through time and in many experiments this is sufficient for them to no longer produce a bubble that could then lead to a crash.

C. Bounded Rationality and Irrationality

The mean trading volume per treatment, period, and level of experience is plotted in Figure 3. If turnover is regarded as a bubble measure, experience clearly leads to a more efficient market. In 26 out of 30 cases, the mean turnover decreases from the inexperienced treatment to the once experienced treatment. Assuming a binomial distribution with a probability of success of 0.5, a random draw would yield this result with a probability of less than 10^{-5}. Interestingly, all four cases where mean turnover increases from the inexperienced to the experienced treatment occur in the DO5/10/15 treatment. Contrary to our conjecture that more option maturity times would increase the efficiency of the market, this measure indicates that the opposite is the case.

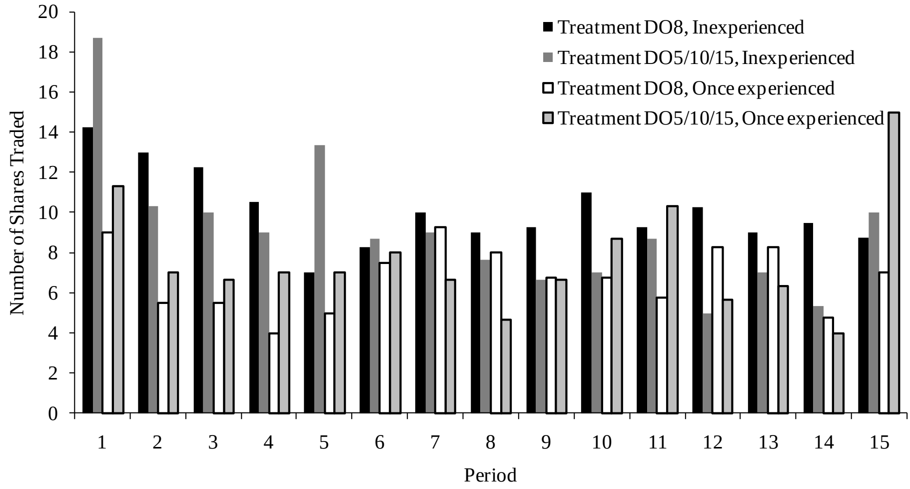


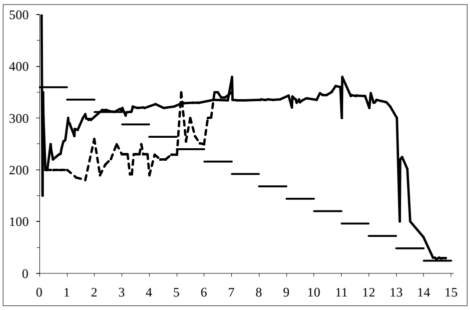
Figure 3. Mean trading volume. The five graphs show, for each treatment and two levels of experience, the mean trading volume over all sessions. Inexperienced subjects have never participated in an experiment of this type and once experienced subjects are the same individuals in the second trading session.

In an attempt to find an explanation for this and the more general observation that the option market does not seem to increase the efficiency of experimental asset market prices, we turn to the answers from our questionnaire. Our sixth question asked whether subjects felt that the option market had helped them in determining how much they would be willing to pay for the stock. The mean answer (on a scale from zero to four, where zero corresponded to “Not at all” and four to “Very much”) was 1.362 (1.404) for the inexperienced (once experienced) subjects in the DO8 treatment and 1.513 (1.333) for the DO5/10/15 treatment, indicating that subjects did not find the option market to be very helpful in forming expectations about future prices.

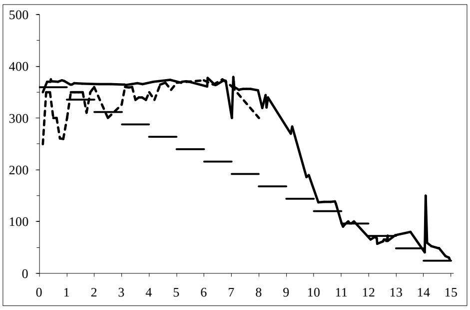
Our first intuition was that the instructions regarding the option market had been unclear. This suspicion is refuted by the relatively high mean answer values on question nine, inquiring how easy it had been for the subject to understand the market mechanism and to form a strategy (scaled between 0, or “Hard” and 4, or “Easy”), which were 2.596 (2.702) for DO8 and 2.564 (2.795) for DO5/10/15, and by the mean answers on question ten, asking how easy it had been for the subject to understand the written and oral instructions, which were 3.170 (3.404) for DO8 and 3.282 (3.462) for DO5/10/15.

In a second attempt to explain why the option market did not aid subjects in their expectation formation, we tried to identify different groups of subjects with regard to their trading strategies and levels of understanding of the market. To do so, we reviewed the questionnaires in detail and solicitated personal feedback in conversations with subjects after our experiments. We found that we can identify two broad groups of traders, which we will designate *naïve* and *rational*.[14] Naïve traders form price expectations based on the current market price and market prices in the same period in previous markets, in line with the Hypothesis of Observation-Based Belief Adaptation. They do not condition their expectation formation on fundamental information about the dividend value of the stock, but learn from their observations of market prices. Rational traders, on the other hand, have fully understood the market mechanism and the fundamental value process of the stock and initially trade based on this prior information. In later periods and rounds, they learn from the observed market prices and at times perform risky arbitrage by purchasing shares above the fundamental value if they expect to be able to earn capital gains and dividends when selling the stock later at similar or higher prices.

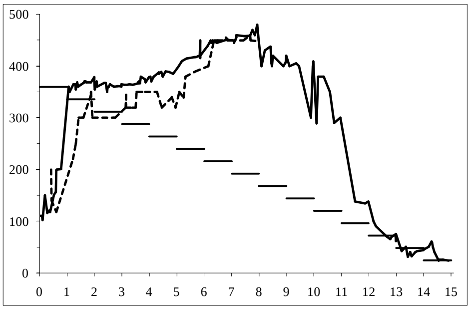
[14] Since these types of traders are not the input for a theoretical model but rather a deduction from empirical observations, subjects do not perfectly conform to these stylized characteristics. Nonetheless, we believe that these cognitive constructs constitute a conceptual simplification of the complex real-world situation, which may aid understanding of the price formation process and could lead to further research questions.



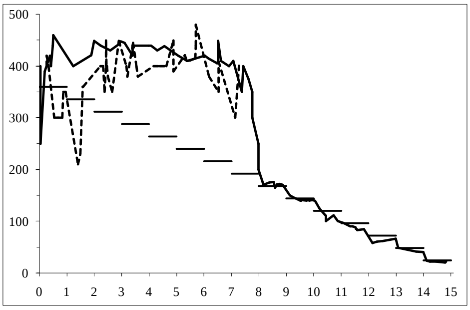
(a) Exp. 1, Inexperienced, DO8



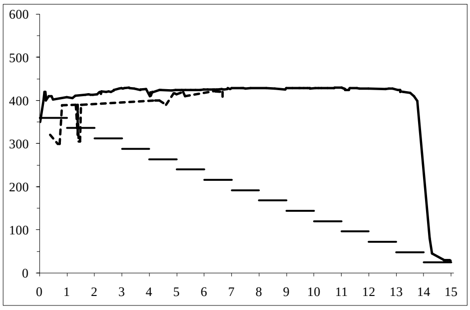
(b) Exp. 1, Once experienced, DO8



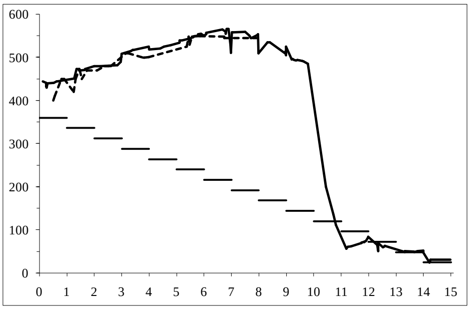
(c) Exp. 2, Inexperienced, DO8



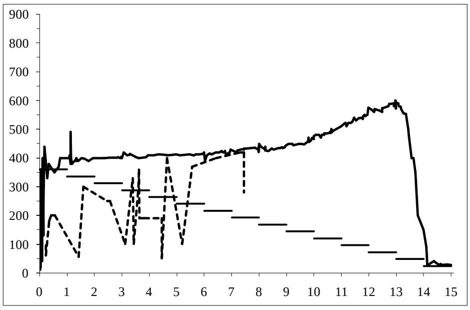
(d) Exp. 2, Once experienced, DO8



(e) Exp. 3, Inexperienced, DO8



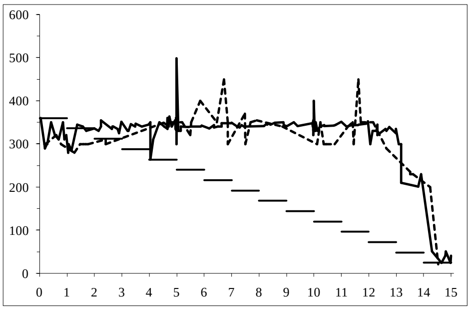
(f) Exp. 3, Once experienced, DO8



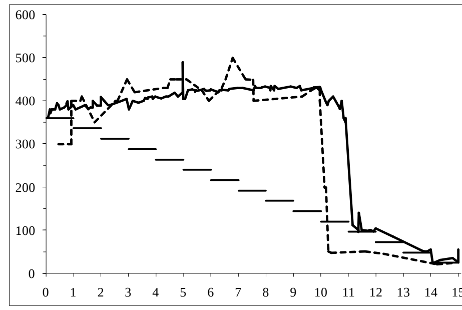
(g) Exp. 4, Inexperienced, DO8

(h) Exp. 4, Once experienced, DO8

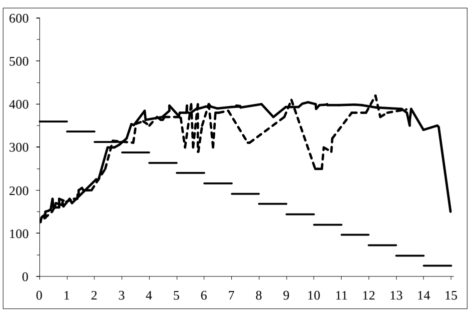
Figure 4. Price plots of experimental sessions. The figure plots the stock price (solid line), option price (broken line), and fundamental value (stepwise decreasing function) in all sessions of the experimental schedule.



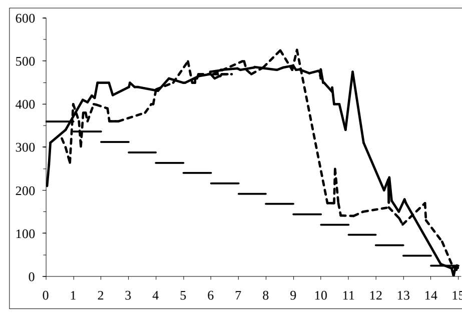
(i) Exp. 5, Inexperienced, DO5/10/15



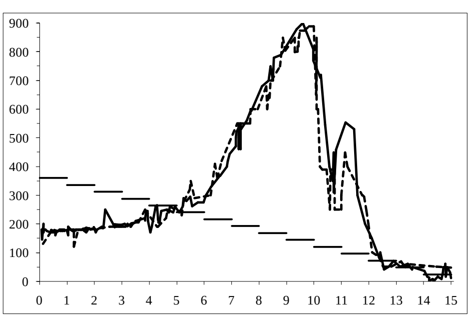
(j) Exp. 5, Once experienced, DO5/10/15



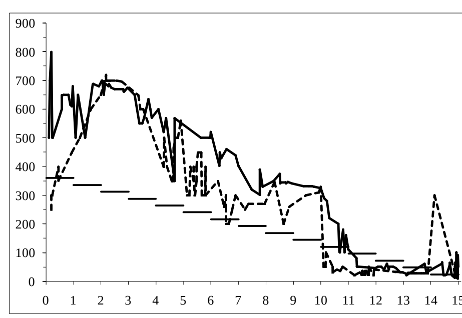
(k) Exp. 6, Inexperienced, DO5/10/15



(l) Exp. 6, Once experienced, DO5/10/15



(m) Exp. 7, Inexperienced, DO5/10/15



(n) Exp. 7, Once experienced, DO5/10/15

Figure 4 cont. Price plots of experimental sessions. The figure plots the stock price (solid line) and the option price (broken line) in all sessions of our experimental schedule.

The presence of a majority of traders we would designate 'naïve' in our experiments leads to naïve option quotes and transactions in the option market, which closely follow contemporaneous prices in the stock market (an overview over all experimental sessions is given in Figure 4). We observe this close link between irrationally high contemporary stock and option prices in most of our experiments, which answers the question regarding the option market's helpfulness from above. The option market *cannot* be informative for the expectations formation of our subjects, because its prices are equally biased as are those of the stock market. Table IV lists a number of statistics designed to underline this observation. If the experimental market had been efficient, it would have exhibited a number of characteristics with regard to the interrelation of the time series of stock and option prices. First, the mean stock price per period should have correlated perfectly positively with the (deterministic and public-information) fundamental value of the stock. Second, the mean option (strike) price per period in the DO8 treatment should not have been correlated with the stock price, since the rational option price in this treatment has a variance of zero, as it is fixed at 192 cent. In the DO5/10/15 treatment, the case is not as obvious. Options with a maturity at the end of period 5 have a rational (strike) price of 264, those with maturity in period 10 have a rational price of 144 and those maturing in period 15 have a rational strike price of 24. The only clear statement regarding the mean period standard deviation of option prices in this treatment is that it is bounded from above by 120.[15]

Table IV

Option Market Efficiency Statistics

This table lists the mean correlation of mean period prices by round, over all sessions, grouped by treatment. Also included is the standard deviation of option prices.

	DO8				DO5/10/15			Both			
Measure	1	2	3	All	1	2	All	1	2	3	All
Correlation Stock – Option	0.81	0.66	0.68	0.73	0.94	0.89	0.91	0.87	0.76	0.68	0.80
Correlation Stock – Fundamental	0.31	0.86	0.93	0.62	-0.04	0.75	0.35	0.16	0.81	0.93	0.52
Correlation Option – Fundamental	-0.91	-0.51	-0.46	-0.68	-0.10	0.77	0.33	-0.57	0.04	-0.46	-0.28
Standard deviation of option prices	73.3	56.2	19.5	59.7	135.2	167.7	151.4	99.8	104.0	19.5	96.4

The results reported in Table IV depart widely from this efficient yardstick. The first content row lists the Pearson correlation between mean period stock and option prices, for all rounds of the two treatments DO8 and DO5/10/15. The stock and option prices are highly positively correlated (Pearson correlation between 0.662 and 0.943[16]). An even stronger sign of the inefficiency of the option market is provided by the option standard deviation results. The mean option price standard devi-

[15] Since the distribution of option transactions between different periods within one round is indeterminate, the variance of an option market populated only with rational traders is also indeterminate. Its upper bound can be arrived at by exploring the transaction pattern that, while still informationally efficient, maximizes the observed option price variance. This pattern is characterized by an equal number of option transactions in periods 1-5 and in periods 11-15, with no transactions in periods 6-10. Assuming that an equal number of transactions take place at the efficient prices of 264 and 24 in periods 1-5 and 11-15, respectively, the resulting (rational) standard deviation would be 120.

[16] Note that the Pearson correlation for the DO5/10/15 treatment is actually consistent with efficiency, since the Pearson correlation would be 0.945 in an efficient market.

ation in the DO8 (DO5/10/15) treatment – which should be zero (less than or equal to 120) – varies between 19.5 and 73.3 (135.2 and 167.7), intervals that do not even contain the efficient figures.[17]

Another manifestation of the bounded rationality of our traders is the structural break between the eighth and ninth period in the DO8 treatment. This break is especially apparent in the sessions with experienced traders, where it is present in three out of the four once-experienced treatments (see Figure 4). Note also that the decline in stock prices began no sooner than the end of period eight in any of the sessions belonging to the first four experiments. Observing this, we conjectured that the option maturity at the end of period 8 is accompanied by a break in subjects' expectations formation regime. As stated before, we gained the impression that during the first half of the experiment, where options on the price of the asset at the end of period 8 could be traded, the attention of our traders with regard to the stock price was focused on the levels of the strike prices of the options they held. In an attempt to further investigate this phenomenon, we designed the DO5/10/15 treatment. We conjectured that the more frequent option maturity dates would cause an earlier return to fundamental values. To our disappointment, this alternative treatment removed the tendency of the structural change to take place between the eighth and ninth period, but did not improve price efficiency overall.

IV. Conclusion

In this article, we report the results of double auction stock market experiments in line with Smith et al. (1988), augmented by the possibility of trade in an option market. Our hypothesis was that trading in the option market induces subjects to form expectations about future prices at an early point in the experiment and to use these expectations to derive a spot price expectation closer to fundamental value by backward induction. We find no support for our hypothesis, as the extent and form of the observed stock price bubbles are comparable to those of earlier baseline experiments documented in the literature. We report some preliminary attempts to explain this finding, which are grounded in the bounded rationality of traders. This approach is in line with the findings of Lei et al. (2001), who prove that subjects in their experiments act irrationally. The Hypothesis of Observation-Based Belief Adaptation is formulated to describe the empirically observed learning behavior of our subjects.

Past studies often conjectured that the inefficiency of prices in experimental asset markets is due to speculation. Such speculation can arise because subjects face uncertainty regarding the behavior of their fellow subjects. In fact, the *actual presence* of irrational traders is not a necessary condition, since the *possibility* of their existence (i.e. the lack of common knowledge of rationality) is a sufficient condition to cause rational traders to trade at prices deviating from fundamental values if they

[17] The standard deviation reported in Table IV was calculated as the mean over all sessions of the standard deviation of all transaction prices within each round.

can expect to reap capital gains by transacting at a later point in time where prices are even farther out of line with fundamentals, a point that is made in Lei et al. (2001). Their finding that irrational traders are present in this type of experiment shows that it is not merely the possibility of their presence that causes bubble-and-crash patterns in groups of fully rational subjects. It is rather their actual presence.

Repeated participation in experimental sessions in a similar setting tends to reduce the bubble phenomenon. In line with the results of Lei et al. (2001) and more recent findings by Haruvy et al. (2007), our experiment suggests that this is caused by a process wherein subjects adapt their beliefs based on observations from previous periods. This fixation on past price realizations and the failure to condition on fundamental value conflicts with explanations which postulate an increase of subjects' innate rationality over repeated participation in SSW-type markets. It seems that, in hundreds of experimental sessions, and despite detailed instructions and control questions, traders are not successful in fully understanding the fundamental value process and its implications for their personal strategic actions.

Appendix A. Translation of and Answers to the Questionnaire

Table A.1

Questionnaire

The questions listed in this table were asked of all participants after each 15-period session. Questions scaled to the numbers 0-4 carried a caption that had one pole designated with a term similar to "Disagree completely" and the other pole with a designation similar to "Agree completely" and gave subjects 5 possible points between these two poles to choose as their answer (0 corresponding to "Disagree completely" and 4 corresponding to "Agree completely"). An "x" in the caption row corresponds to one session of prior experience for the subjects.

Question	Scale	Mean			
		DO8	DO8x	DO5/10/15	DO5/10/15x
What was your strategy during the experiment?	Open/Text				
Did you change your strategy during the experiment and if yes, why?	Open/Text				
What do you believe was the strategy of the other subjects?	Open/Text				
Do you think that you acted rationally and that you were able to maximize your profit?	0-4	2.149	2.468	2.154	2.103
Did you at any time mistype something? If yes, please describe briefly when and how this mistake occurred!	Open/Text				
Did the option market help you gauge how much you would be willing to pay for the stock?	0-4	1.362	1.404	1.513	1.333
Compared to the average player, how successful do you think you were?	0-4	1.787	2.021	1.872	1.692
What do you think is the reason for your having performed better/worse?	Open/Text				
How easy was it for you to understand the market mechanism and prepare a strategy?	0-4	2.596	2.702	2.564	2.795
How easy was it for you to understand the written and oral instructions?	0-4	3.170	3.404	3.282	3.462
How could the experiment be made easier to understand and/or what could be improved?	Open/Text				
Which studies have you completed or are currently enrolled in?	Open/Text				
Your age?	17-99	25.23	25.19	24.38	24.33
Your sex?	Female/Male	42.6[¥]	42.6[¥]	28.2[¥]	28.2[¥]
Highest level of education completed?	* see below				
Is this your first laboratory experiment?	Yes/No	66[†]	-	87[†]	-
How good would you say is your knowledge of finance and capital markets?	0-4	2.234	2.234	2.103	2.077
Have you traded stock in the past?	Yes/No	48.9[†]	48.9[†]	41[†]	41[†]
Have you traded options in the past?	Yes/No	12.8[†]	12.8[†]	7.7[†]	7.7[†]
How often have you participated in a similar experiment involving trading of stock in a market?	Number	0.255	1.255	0.154	0.615
How often have you participated in a similar experiment involving trading of stock and options in a market?	Number	0.064	1.064	0.051	0.538

* Possible answers were: Elementary school, Apprenticeship, Secondary school, Grammar school, Bachelor, Master, Doctorate. † Percentage of "Yes" replies. ¥ Percentage of female subjects.

Appendix B. Explanation of Bubble Measure Calculations

This section explains the origin of the bubble measures reported in Table III. From Ackert and Church (2001), we report the bubble measures found in their Table 3, p. 17, columns 3 (*Duration*), 4 (*Amplitude*), and 7 (*Turnover*).The measures from PS are taken from their Table 5, p. 521. Their *Amplitude* is reported in columns 2 and 5, *Duration* in columns 3 and 6, and *Turnover* in columns 4 and 7. The sample size is taken from Table 4 and the notes of Table 4, p. 519. In addition to the sample size listed for the PS baseline experiments in our Table III, three baseline experiments are mentioned there, but it is not made clear whether they were conducted with inexperienced or experienced subjects. Hence, these three experiments are included in the sample size number of neither the inexperienced nor the experienced measures. Regarding Van Boening et al. (1993), *Amplitude* is taken from Table 1, p. 181. We calculate the mean of the price amplitude (column 2) for series 1 and series 2 (the two double auction series), divided by 3.75, which is the intrinsic value of the share in period 1 of their experiment. This serves to transform their amplitude measure into *Amplitude*, as reported in section II.A. of this article. The same calculation is performed for *Turnover* (column 4).

Appendix C. Subject Portfolio Mappings

Table C.1

Initial Trader Portfolios Over All Sessions

Initial endowment for each subject, given the number of subjects, over all rounds. Portfolio A consisted of 1 stock and 945 cents cash, portfolio B of 2 stock and 585 cents cash and portfolio C of 3 stock and 225 cents cash. Each portfolio had an expected value of € 13.05 and was accompanied by a loan of € 10, to be repaid at the end of the round.

Subject	11 Subjects		12 Subjects		13 Subjects		14 Subjects	
Round:	1	2	1	2	1	2	1	2
1	C	C	C	C	C	C	C	C
2	C	B	C	B	C	B	C	B
3	C	A	C	A	C	A	C	A
4	A	C	C	B	C	B	C	B
5	A	B	A	B	A	C	A	C
6	A	A	A	C	A	B	A	B
7	B	C	A	A	A	A	A	A
8	B	B	A	A	A	C	A	C
9	B	A	B	A	B	C	B	C
10	B	B	B	C	B	B	B	B
11	B	B	B	B	B	A	B	A
12			B	C	B	A	B	A
13					B	B	B	B
14							B	B

ACKNOWLEDGMENTS

For the original idea of employing digital options in a Smith, Suchanek and Williams (1988)-type experiment, we thank Hubertus Hofkirchner. Our thanks furthermore goes to Lucy Ackert, James Ang, Nicole Höhenberger, Ron King, Ulrike Leopold-Wildburger, Roland Mestel and Peter Steiner for help and invaluable comments, to Dave Porter for providing detailed data on Porter and Smith (1995), to Dan Gode and Shyam Sunder for providing detailed data on Gode and Sunder (1993), to Alexander Brauneis for organizing two experimental sessions at the University of Klagenfurt, and to Stefan Schmid and Urs Fischbacher for their help with the z-Tree software. We particularly thank Simon Gächter for inspiring and encouraging us to take up experimental research during conversations at his seminar at the European Forum Alpbach 2005 and his presentations at the Graz Schumpeter Lectures 2006.

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