Real Options: Experimental Evidence

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Abstract

Empirical testing of the real options theory has been very limited. This is primarily due to various inherent problems with obtaining field data for many components of real options theory. This paper utilizes *experimental methodology* to generate the data. The advantage of the experimental approach is that it enables the investigator to generate reliable and replicable data in a controlled environment. The results of the experiment indicate that fundamental insights of real options theory are not evident to individual investors. The majority invested to early and thus failed to recognize the benefit of the option to wait. However, when the investors had to compete with others for the right to invest, their bids generally reflected the value of the embedded option. Furthermore, as predicted by the theory, their bids increased with greater uncertainty about future cash flows from the investment.

1. Introduction

The application of option theory has dramatically altered the way researchers model investment decisions. The study of real options has been one of the most fruitful areas of research. It has been applied to various investment problems including real estate development (Titman, 1985; Williams, 1991; Childs, Ott and Riddiough, 1996), lease contracts (McConnell and Schallheim, 1983; Grenadier, 1995 and 1996), mortgage default and refinancing decisions (Kau and Keenan,1995), oil exploration (Paddock, Siegel and Smith, 1988), and research and development (Dasgupta and Stiglitz, 1980) .

In spite of its significant practical implications for various investment decisions, empirical testing of real options has been scarce. This is primarily due to the problems that researchers face in obtaining the necessary data. It is intrinsically difficult to find reliable data on such components of the real options approach as the current and future value of the underlying asset and the variability of value. Furthermore, most of the components of options models are exposed to subjective valuations. Also, the value of the option itself is often embedded in the total value of the asset, for example undeveloped land, and is not directly observable. As a result, previous empirical studies of real options had to either estimate or use proxies for many of these inputs. It is not surprising, therefore, that there have been very few empirical tests of real options models (one recent example is Quigg, 1993).

This paper offers an alternative methodology to test some of the fundamental insights of the real options theory. To overcome data problems, laboratory experiments are used to generate the data for the analysis. Although experimental methodology has been widely used in economics and finance, it has not been used by researchers to test the fundamental premises underlying real options

theory.[1] Therefore, the current paper has two contributions: One is the application of the experimental methodology to generate the data, and the other is an empirical test of a theory that has crucial implications for investment decisions.

Two sets of experimental sessions were conducted. The first set included sessions designed to test the optimal timing of investment decisions. In these sessions, while the Net Present Value (NPV) of investing immediately was positive, it was optimal to delay the investment decision until the uncertainty about future cash flows was resolved. The second set included sessions where the subjects had to bid for the right to play the investment game. These sessions were designed to measure the premium associated with the real option component of an investment and how this premium was correlated with the uncertainty about the future cash flows from the investment.

The results of the experiments offer mixed evidence for the theory. In general, the observed behavior of the subjects/investors diverged from the theoretical predictions with respect to timing of investment decisions. Majority of the investors chose to invest too early and failed to recognize the benefits of delaying the investment. However, when the subjects had to bid for the right to invest in a project, their bids generally reflected the value of the real option embedded in that project. Although the bids were initially overoptimistic, through experience they converged to theoretically predicted levels. Furthermore, the bidding behavior supports the well-known result in the options theory that greater uncertainty about future cash flows results in an increase in the value of the project.

An important difference between the two sets of experimental sessions is that the timing decisions were determined by each investor individually, while the bidding decisions involved

[1] One exception is Rauchs and Willinger (1996) which looks at the portfolio choice of subjects between a risk-free asset and a risky asset and examines how the subjects' choices relate to the amount of information they expect to

competition with other investors. Thus, one implication of our results is that while individual investors tend to use the NPV approach and fail to recognize the value of real options in even a very simple setting, competition in the market brings the asset prices to the levels that capture the real option value of the asset.

The next section of the paper reviews the major results of the real options theory that will be tested in the experiments. Section 3 provides an overview of the experimental methodology while Section 4 describes the design of the experiments conducted. Results of the experiments are reported in Section 5. Section 6 offers some concluding remarks.

2. Real Options

Real options approach has challenged some of the conventional criteria for investment decision-making. It has enabled investors to recognize that it might not be optimal to invest in a project even if the NPV of the project is positive. When investments are not fully reversible and decisions to invest can be postponed, there may be a benefit in waiting to invest until the uncertainty regarding the future cash flows is resolved. While the NPV decision rule treats an investment decision as "either now or never," the real options approach recognizes the value of the timing of the investment as well. It recognizes that when a firm commits to an irreversible investment, it gives up the possibility of waiting for new information to arrive that might affect the attractiveness of the investment and the possibility of disinvestment should the market conditions deteriorate. As a result, even if the NPV of investing right away is positive it may be optimal for the firm to delay the investment and keep the option alive until the uncertainty is resolved. Failure to recognize the value

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receive about the risky asset in the future.

of the option will lead to suboptimal investment decisions.

Consider the investment game, Game T1, in Figure 1a. There is no uncertainty in period 1 during which the investment generates a certain income of $2,500. There are two possibilities for the income in period 2, either 22,500 or 7,500, each with equal probability. Similarly, depending on what happened in period 2, period 3 has two possible outcomes. If the second period income turns out to be 22,500, then the third period income will be either 45,000 or 0, each with equal probability. On the other hand, if the second period income turns out to be 7,500, then the third period income will be either 15,000 or 0, each with equal probability. Given the irreversible nature of the investment, an investor therefore has three strategy choices: 1) Invest in period 1 and remain invested for all three periods, in which case the investor earns 2,500 in the first period, either 22,500 or 7,500 in the second period, and either 45,000, 15,000 or 0 in the third period. 2) Wait until the uncertainty about the second period's income is resolved and then decide whether or not to invest in period 2. If the investor invests in period 2 after the income for period 2 is observed to be 22,500, then s/he earns 22,500 plus the uncertain income of either 45,000 or 0 in the third period. Similarly, if the investment is taken after the second period income is observed to be 7,500, then the investor earns 7,500 plus either 15,000 or 0 in the third period. 3) Wait until the uncertainty about the second and third periods' income is resolved and then decide whether or not to invest in period 3.

The investment Game T2 of Figure 1b is identical to Game T1 except for the cash flows in the second period. In both games, it costs 25,000 to invest in the project, regardless of the period in which the investment is taken.

To present the above problem at a more general level, let I_1 be the certain income from the investment in period 1, P_{jt} be the probability that the income in period t will be I_{jt} where t = 2,3 and

j is the index referring to different possible income levels in that period, and let *C* be the cost of investment. For simplicity, assume no discounting and risk neutral investors.[2] Each investor needs to decide whether to invest in the project right away or wait for one or two periods. If the investment is taken right away, the expected value of the investment is given by the following:

$$(1) \qquad EV(1) = I_1 + \sum_t \sum_j P_{jt} I_{jt} - C \qquad t = 2,3.$$

If the investor decides to wait for the resolution of the uncertainty about the second period's income and delays the investment until period 2, the expected value of the investment becomes:

$$(2) \qquad EV(2) = \sum_j P_{j2} \, max\{0, I_{j2} + \sum_i (P_{i3}| I_{j2}) I_{i3} - C\}$$

where $(P_{i3}| I_{j2})$ is the probability of income I_{i3} in period 3 conditional on the realized income in the previous period. Note that, in return for giving up the first period's income, the investor now gains the flexibility of not investing if the value of EV(2) is negative at the realized value of I_{j2}.

Similarly, the strategy of delaying the investment until period 3 gives the expected value of the investment as

$$(3) \qquad EV(3) = \sum_j P_{j3} \, max\{0, I_{j3} - C\}.$$

Each of the three expected value terms above are as of period 1. The investor must decide how long to wait before the resolution of any uncertainty about the future cash flows.

Clearly, the optimal timing of the investment will be determined by the maximum of the

[2] Risk aversion and arbitrage play an important role in option theory. The simplified version here, however, does not require risk aversion or a riskless investment alternative for the investors.

three expected value terms above. Applying the above terms to the parameters of the investment Game T1 of Figure 1a, we find that EV(1)=7,500, EV(2)=10,000 and EV(3)=5,000. Therefore, the optimal strategy in Game T1 is to wait until period 2 and invest in period 2 only if the income in period 2 is 22,500 (and do not invest in the project at all, otherwise). For the investment Game T2 of Figure 1b, on the other hand, we find that EV(1)=1,250, EV(2)=2,500 and EV(3)=5,000. Therefore, the optimal strategy in the investment game of Figure 1b is to wait until period 3 and invest in only if the income in period 3 is 45,000. Note that in both investment games NPV of investing right away in the first period is positive, EV(1) > 0. However, it is even more profitable to wait until the uncertainty about the second period's or both second and third periods' incomes is resolved.

Another important message of the real options approach is that uncertainty creates opportunities. Managers / investors should welcome, not fear uncertainty. This is a crucial difference from NPV analysis. When a company is fully invested, as NPV analysis assumes, uncertainty has a negative effect on the attractiveness of the project. When a company has only an option, however, it is exposed to the upside risk, but not the downside risk. As a result, the investor with an option prefers a greater uncertainty about the future returns because s/he can exercise the option if returns come out at the top, or back out otherwise.

To see this, consider the four games illustrated in Figure 2 where investors have to bid for the right to invest in a project. These investment games could represent vacant land where potential buyers have to bid to purchase. If developed, the land generates an income of 2,500 in the first period. The income in the second period in Game B1 will be either 45,000 or 15,000, each with equal probability. The optimal investment strategy in Game B1 is to wait until the resolution of the uncertainty for the second period income and then decide whether or not to invest. The expected

value of the investment, thus the maximum amount that investors should be willing to bid for the lot, is ½ (45,000-25,000)=10,000. Next, consider Game B2 where there is a greater uncertainty about the future cash flows; the income in the good state is raised to 50,000 while the income in the bad state is reduced to 10,000. However, this increased uncertainty leads to a higher expected value of the investment. The optimal strategy is again to delay the investment until period 2. The maximum amount that investors should be willing to bid for the lot now is ½ (50,000-25,000)=12,500. In Game B3, the uncertainty is reduced so that the second period payoffs are either 40,000 or 20,000. It is again better to wait for the resolution of the uncertainty about the second period's income. Reduced uncertainty in Game B3 lowers the value of the investment to ½ (40,000-25,000)=7,500. Finally, Game B4 is identical to Game B1 except that Game B4 does not offer the investors the option to delay the investment until period 2. Investors have to invest either in period 1 or never. The elimination of the real option in Game B4 results in an expected value of 2,500 + ½(45,000+15,000) – 25,000 = 7,500. Therefore, the value of the real option in Game B1 is 2,500, the difference between the expected value of the investment in Game B1 versus B4.

Although the arguments of real options have been proven rigorously by the theoretical studies, it is not clear if investors would indeed delay a project with a positive NPV or if an investor would indeed prefer greater uncertainty. Based on the above discussions and using the investment games presented in Figures 1 and 2, the following hypotheses are tested in the experiments.

The first hypothesis concerns the optimal timing of the investment: When "waiting" is the optimal strategy, do investors postpone the investment decision until uncertainty is resolved even if the NPV of immediate development is positive? More specifically, we test the following:

> ***Hypothesis 1:*** In investment Game T1, investors wait until the uncertainty about the second period's income is resolved. In investment Game T2, investors wait until the uncertainty about both the second and third periods' incomes is resolved.

The second hypothesis relates to the real options premium of an investment opportunity. When investors have to bid for an investment with uncertain future cash flows, do they recognize the value of the option and adjust their bids upward?

> ***Hypothesis 2:*** Investors should bid up to 10,000 for the investment in Game B1. In Game B4 where the option to wait is eliminated, they should bid no more than 7,500.

The third hypothesis is about the seemingly counter-intuitive result of the options theory that an increase in the uncertainty surrounding the future cash flows increases the value of the option, hence the value of an asset with an embedded option.

> ***Hypothesis 3:*** Investors should bid up to 10,000 for the investment in Game B1, up to 12,500 in Game B2, and up to 7,500 in Game B3.

These hypotheses were tested with laboratory experiments where human subjects were recruited to make investment and/or bidding decisions using the games of Figures 1 and 2. The bidding and/or investment decisions of the players determined their cash earnings from the experiment. Thus, the subjects had monetary incentives to make investment decisions that maximized their earnings. Before we present the experimental design and the results, a brief discussion of the experimental methodology is provided in the next section.

3. Why Laboratory Experiments?

This section of the paper explains the advantages of laboratory experiments and why they have become popular with researchers in economics and finance, as well as numerous other fields.

A primary advantage of laboratory experiments is that they allow the researcher to have control over the data. The researcher can design the game to induce changes in desired variables and hold the other variables constant, thus evaluating and comparing alternative theories and policies. Although econometricians sometimes manage to clearly identify the effects of desired variables from the rest of the factors, they do not have the ability to control the environment in generating their data sets.

Experimental methodology also enables the researcher to avoid data aggregation problems. This is a common problem with empirical tests of option-based models. In an experimental setting, the researcher can observe the behavior of each individual investor.

Another advantage of an experimental approach is that in cases where collection and verification of field data is expensive, it can serve as a less costly alternative to generating the desired data. Experimental methods also may offer more reliable data, because the field data are usually collected not by the researcher for scientific purposes, but by businesses and/or government agents for their own purposes.

The main advantage of experimental methodology, however, is that its data are replicable. Field data are generated from events that occurred at a specific time in a specific place. Due to the constantly changing nature of these settings, it is very difficult for other researchers to replicate a field data set, therefore making it difficult to verify the accuracy of the data and the accuracy of the

findings. Since laboratory data are generated in controlled laboratory conditions, it is easier to reproduce the experiment and replicate the results.

In addition to the above advantages, laboratory methodology is sometimes the only feasible way to test a theory. This happens when data from existing markets cannot be collected, because it is impossible to find markets that match the assumptions of the theory, or the data are available but not in a form that would enable us to differentiate among alternative theories. This problem is particularly manifested in individual choice problems and game theoretical analysis. These models are either impossible or very difficult to evaluate with field data.

The questions examined in the current study are good examples where the reliable field data are difficult to obtain. Option valuation models would require data on the current and future value of the underlying real asset, optimal use of the asset, investors' expectations about the future cash flows and the stochastic process that captures the changes in future cash flows. Such information is either difficult or impossible to obtain or estimate from the field data. However, as will be seen in the next section, such data can be easily generated and controlled for in a laboratory experiment.

4. The Experimental Design

The key to a successful experimental analysis of real options is a careful design of the investment game. The design needs to be simple, yet at the same time it needs to capture the essential elements of the real options theory and offer a proper incentive mechanism for the players to treat it as a real investment game.

We conducted multiple experimental sessions in order to test different aspects -as stated in the questions above- of the real options approach. A single aspect/parameter of the investment game was changed from one session to another so that a comparison of the two sessions would yield the

impact of that aspect/parameter. The subjects for the experiment were recruited from the undergraduate classes at Penn State University and they earned cash for participating in the experiment. Their earnings directly depended on their investment decisions, thus providing them with monetary incentives to make optimal investment decisions.

Two sets of experimental sessions were conducted. The first set involved two sessions that were designed to test the timing of investment decisions. Investment games in these two sessions involved 3 periods. We refer to these sessions as "Timing sessions" and label them as Session T1 and Sessions T2. The investment game used in Session T1 was based on the investment game of Figure 1a. The investment game in Session T2, based on the investment game of Figure 2b, was identical to that of Session T1 except that the second period payoffs were changed from 22,500 and 7,500 points to 7,500 points to 10,000 points, respectively. As indicated earlier, while the optimal strategy in Session T1 is to wait until the second period and invest if the payoff in the second period is 22,500 points, the optimal strategy in Session T2 is to wait until the third period and invest only if the payoff in the third period comes out as 45,000 points. Thus, sessions T1 and T2 will be used to test Hypothesis 1.

The second set of experimental sessions involved four sessions that were designed to test how much the investors would bid for an investment opportunity with and without a real option, and how a change in the uncertainty of future payoffs would affect the premium that the investors would be willing to pay for the real option. These sessions will be referred to as the "Bidding sessions" and will be labeled as Sessions B1-B4. As displayed in Figure 2, each of the Bidding sessions involved a simple, two-period investment game with a certain first period income and an uncertain second period income. In Session B1, the investment involved a second period income of either 45,000 or 15,000, each with equal probability. The second period incomes were changed to 50,000 and 10,000

in Session B2, and to 40,000 and 20,000 in Session B3. Session B4 was identical to Session B1 except that the investors did not have the option of waiting for a period; they could either invest right away in period 1 or never. Thus, the comparison of B1 and B4 would indicate the value that investors assigned to the value of the option to wait and will enable us to test Hypothesis 2. Similarly, a comparison of the data from sessions B1-B3 will be used to test Hypothesis 3.

The cash flows from the project in period 2 of Games T1 and T2 and the cash flows in periods 2 and 3 of Games B1-B4 were determined by dice rolls. At the end of the first period in T1 and T2 sessions, and at the end of first and second periods in B1-B4 sessions, one of the subjects (in a rotating manner) was asked to roll a dice. If the dice roll came out as even number (i.e., 2, 4 or 6), then the cash flow for that period was the cash flow given by the upper branch of the corresponding figure for that period. Similarly, an odd dice roll resulted in the cash flow given by the lower branch of the corresponding figure.

Given the possibility that the subjects may not possess a clear understanding of the investment game after just reading the instructions, we wanted to give the subjects a chance to gain experience with the investment game. For this reason, we had the subjects in each session play the investment game of that session a number of times. More specifically, subjects played the investment game 18 times/rounds in each session. The first three rounds of each session were designated as practice rounds. The purpose of the practice rounds was to familiarize the subjects with the experimental procedures. The earnings in the practice rounds were hypothetical, thus the subjects' choices in the practice round did not affect their actual earnings. At the end of each practice round we gave subjects another opportunity to ask questions.

The sessions were conducted in January 2001 at the Pennsylvania State University. Subjects were recruited through e-mails. Interested students could go to a specially designed website to sign up for the experiment.[3] In order to eliminate any potential effects of experience, the software did not allow anyone to sign up for more than one session.[4]

In each session the subjects were seated in a large computer lab. They were read a set of instructions and given an opportunity to ask questions. Although each subject was given a copy of the instructions, a monitor read the instructions aloud so that the subjects knew that they were all being given the same instructions and all being asked to play the same investment game.

Each of the six sessions involved 20 subjects.[5] A copy of the instructions for Session T1 and Session B1 can be found in the appendix. In each round of each session, subjects recorded their strategy choices and the resulting earnings on a decision form that they were provided. Monitors checked each subject's recording of his/her decisions and calculations of earnings at the end of every round. The next round did not begin until the monitors had verified that all the subjects had calculated their earnings correctly. In timing sessions of T1 and T2, subjects had to choose in which period to invest in the project. In bidding sessions of B1-B4, subjects first had to bid for the right to invest in the project, and those who won the bidding then had to decide in which period to invest in the project. The subjects could bid any integer amount between 0 and 40,000. The subjects submitted their bids to a monitor using the bidding forms provided. Once all the bids were

[3] The java based software at the website allowed a pre-specified number of students to sign up for each session and sent out e-mails to the subjects the day before the experiment to remind them about the experiment.

[4] The purpose of this is to eliminate any experience differentials among the subjects. Otherwise, it can be claimed that any difference between the outcomes of earlier and later sessions is due to the fact that subjects who participated in multiple sessions gained experience in earlier sessions, and this experience induced them to follow a different strategy in later sessions.

[5] The only exception is Session T1which included 14 subjects. The recruitment software was instructed to allow 28 subjects to sign up for each session against the possibility of no shows (if more than 20 subjects showed up, a show-up fee of $5.00 was paid to those who were turned back). For Session T1 only 14 subjects showed up.

submitted, we ranked the bids from the highest to the lowest and the top 10 bidders earned the right to participate in the investment project. Each of the top 10 bidders had to pay the 10th highest bid for the right to invest.[6] In the case of a tie for the 10th spot, a monitor randomly drew from among the bidding forms that tied for the 10th spot.

Our inspection of the subjects' calculations at the end of each of the three practice rounds convinced us that the subjects understood the game before the beginning of the fourth round. We also gave the subjects a questionnaire at the end of each session. In response to one of the questions in the questionnaire, all subjects reported that they had a clear understanding of the instructions.

In the timing sessions T1-T2, the subjects started the session with an initial balance of 10,000 points. The initial balance in the Bidding sessions B1-B4 was set at 15,000 points. The initial balance also acted as the risk-free return in that the subjects could ensure themselves this return by simply being inactive (bidding zero and/or not investing at all in each round of the session). Subjects earned or lost additional points through the outcome of their investment decisions. At the end of each session, one of the rounds 4-18 was randomly selected by each subject[7] and that subject's point earnings / losses in the randomly selected round was added to / subtracted from the initial balance. The subject was then paid $1.00 per 1,000 points she/he netted in that round. The purpose of basing subjects' earnings on a randomly drawn single round, rather than basing it on the average of all rounds, was to increase the significance of the decisions made in each round. Each session lasted about 90 minutes. Subjects' earnings varied from zero (i.e., a total loss of the initial balance) to

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[6] The alternative is to have each winning subject pay his/her bid. Theoretically, both auction structures should result in the same bidding strategy for the subjects. The reason for the choice of the 10th bid as the price to be paid by each winning bidder in the experiment is that 10th bid is the median bid (recall that there were 20 bids), hence it is a better representative of the market-clearing price than any other bid.

[7] Each subject was asked to draw from a deck of cards numbered 4 through 18.

$55.00.[8] Such a variance in earnings indicates that subjects' earnings were sensitive to their investment decisions.

Clearly, the investment games of Figures 1 and 2 abstract from the institutional details of real options embedded in most investment projects. However, the essential and interesting features of these investments are captured in these games. Whether outcomes are sensitive to institutional details is another question that could be investigated experimentally, but is beyond the scope of the current paper. Our experiments were designed to capture important aspects of the real options theory in games as simple as possible.

5. Experimental Results

We begin this Section by comparing the observed outcomes in T1 and T2 sessions with the theoretical predictions.[9] Figures 3a, 3b, and 3c graph the proportion of the time investors in sessions T1 and T2 chose to invest in periods 1, 2 and 3, respectively. The averages across rounds are summarized in Table 1 below.[10] The proportions for period 2 are the proportion of investors who waited for a period and chose to make the investment in period 2 after the realization of the income level of 22,500 in Figure 1a and 7,500 in Figure 1b (i.e., the income level in period 2 that results in a positive NPV). Similarly, the proportions for period 3 are the proportion of investors who waited for two periods and chose to invest in period 3 after the realization of the income level of 45,000 in

[8] If a subject's net earning was a loss, the subject was not asked to make any payment to the experimenter. At the end of the experiment, a $5.00 show up fee was paid to each subject, thus each subject walked away with at least $5.00.

[9] The data from the practice round is excluded from all calculations in this section. A complete set of the data is available upon request.

[10] The last 5 rounds will be reported separately from all 15 rounds in order to see if the "experience" in the first 10 rounds led to a change in behavior in the last 5 rounds.

period 3 in Figures 1a and 1b.[11]

As discussed earlier, the theory predicts no investor should invest in period 1 of either session. It is clear from Figure 3a and Table 1 that a significant proportion of investors chose to invest in period 1. A t-test rejects the hypothesis that the proportion of investors who invested in period 1 is zero in either session.[12] The only exception is with respect to the final five rounds of Session T1 where the ratio dropped below 20%, and a t-test indicates that the ratio in the final 5 rounds was not significantly different than the predicted ratio of zero.

Table 1: Proportion of Investors in Sessions T1 and T2 who chose to Invest in

	Period 1		**Period 2**		**Period 3**	
Rounds:	All 15	Final 5	All 15	Final 5	All 15	Final 5
Mean-Session T1:	0.33	0.17	0.19	0.31	0.09	0.17
Mean-Session T2:	0.35	0.34	0.13	0.07	0.34	0.33

The theory again lacks support when we look at the proportion of investors choosing to invest in Period 2 following a positive NPV income discovery in Period 2 (i.e., 22,500 in Session T1 and 7,500 in Session T2). The theory predicts that all of the investors in Session T1 and none of the investors in Session T2 should invest in period 2 following a positive NPV income. T-tests verify what is already obvious from Table 1 that the observed proportions are significantly different than the theoretical prediction.

The prediction with respect to Period 3 is that all investors in Session T2 should have waited until Period 3 and invest if the Period 3 cash flow is observed to be 45,000. Although slightly more

[11] The investors were rational in that they did not delay their investment only to invest in a period after the announcement of an income for that period that produced a negative NPV.

[12] The number of observations for the t-tests is taken as the number of subjects in that round rather than as the total number of decisions made across rounds. This is "safer" in that the observations across rounds are less likely to be independent than the observations across subjects.

than 1/3 of the investors in Session T2 waited until period 3, this ratio is significantly less than the theoretical prediction.

With the exception for the final 5 rounds of Session T1, the data did not support the point predictions of the theory. We can also compare the two sessions with each other in order to see if the proportions of investments in the two sessions are at least ranked in the order predicted by the theory. The Wilcoxon two-sample test shows that the difference between the percentages of investors investing in period 1 in the two sessions is insignificant overall. However, this difference becomes significant for investments in period 1 in the last 5 rounds where there is more investment in Session T2 than Session T1. Also, a significantly higher proportion invested in period 3 of Session T2 than Session T1.

We now turn to the four Bidding sessions. The data on bidding sessions is displayed in figures 4a and 4b. Figure 4a presents the winning bid (i.e., the 10^{th} highest bid or the median bid) while Figure 4b displays the average bid in each round of each session. The mean of the average winning bid and the average overall bid across rounds are as follow:

Table 2: Winning Bid and Average Bid in Sessions B1-B4

	Winning Bid	**Average Bid**
Session B1:		
All 15 Rounds	5,924	7,788
Final 5 Rounds	4,600	6,658
Session B2:		
All 15 Rounds	17,272	17,949
Final 5 Rounds	12,117	12,674
Session B3:		
All 15 Rounds	7,557	10,235
Final 5 Rounds	7,440	9,662
Session B4:		
All 15 Rounds	12,213	12,349
Final 5 Rounds	8,420	9,491

Recall that the theory predicts that subjects should bid up to 10,000 in Session B1, 12,500 in Session B2, 7,500 in Session B3 and 7,500 in Session B4. Except for the first session where the investors bid significantly below the theoretical levels, the average bids in the final five rounds in Sessions B2-B4 are close to the theoretically predicted levels (recall that subjects were allowed to bid in the range of 0-40,000 points). A t-test of the differences between the average bids given in Table 2 and the theoretically predicted bids for sessions B2-B4 indicate that none of the differences are statistically different than zero at 5 percent level. The bids also support the prediction that a greater uncertainty leads to a higher investment value (Hypothesis 3). A comparison of the bids in Sessions B1 and B4, however, contradicts the theory that adding real options to an investment increases the value of the investment (Hypothesis 2). On the contrary, the subjects bid more for the investment when the real option component of the investment was taken away in Session 4. This is related to the fact that subjects in Session 1 bid significantly below the theoretically predicted level.

The observed behavior in Session 1 stands out as being different than the other sessions. One could argue that the bidding behavior in Session B4 can be explained by risk aversion. Theoretical predictions were based on risk neutrality while the subjects can be risk averse. There is no reason, however, for the 20 subjects in Session B4 to be more risk averse than the subjects in other sessions.

Although it is irrational, there is a chance that subjects' bidding decisions in a session were influenced by the outcome of the dice roll in the previous rounds of that session. It turns out that 60% of the dice rolls (i.e., in 9 out of 15 rounds) in Sessions B2 and B4 were even while only 40% of the dice rolls (i.e., in 6 out of 15 rounds) in Sessions B1 and B3 were even. One might argue, therefore, that the reason for the observed bids in Session B1 to be below those of B4 is the occurrence of more even dice rolls in Session B4. There is a somewhat weak anecdotal evidence from the written survey conducted at the end of each session that some players' decisions in a round

might have been affected by the dice rolls in previous rounds. This does not, however, explain why the observed bids in Session B3 were in line with the theory even though it too had 40% occurrence of even dice rolls. A possible explanation lies in the distribution of the even dice rolls in these two sessions. While the even dice rolls are scattered evenly across rounds in Session B3, there were only one even dice roll in the first seven rounds of Session B1. Observing six odd dice rolls in the first seven rounds might have influenced the players' willingness to bid for the remainder of the B1 session. In fact, the initial bids in Session B1 were significantly higher than the session averages reported in Table 3. The average overall bid in the fourth round was 12,177.50 and the winning bid was 9,000.

Since the bidding sessions included only 2 periods, it would be interesting to see if the subjects with a winning bid in these simpler sessions made the right timing decisions compared to the more complicated timing sessions. Recall that the optimal strategy in each of sessions B1-B3 is to wait until period 2 to decide whether or not to invest. Table 3 displays the percentage of investors who violated the optimal strategy and chose to invest in period 1.

Table 3: Proportion of Investors in Sessions B1-B3 who chose to Invest in Period 1

	All 15 Rounds	Final 5 Rounds
Session B1:	0.24	0.16
Session B2:	0.42	0.22
Session B3:	0.69	0.78

Clearly, the subjects once again failed to exercise optimal timing in their investment decisions.

One other observation about the data is worth mentioning. Subjects' decisions changed through time. Initially, subjects were bidding very aggressively for the right to invest in the project. The winning bids in the fourth round of Sessions B1 through B4 were 9,000, 20,000, 9,050 and 20,000 respectively. By the final round, these bids reduced to 5,000, 11,125, 7,750 and 7,000,

respectively. The bids did stabilize in the last 3-5 rounds. In other words, through experience the subjects learned to have more realistic expectations/valuations of the asset. It is interesting, perhaps not surprising, that the initial behavior of the subjects were driven by over optimism, not pessimism. This is in line with the conventional wisdom that inexperienced investors in financial markets tend to be more aggressive and optimistic than the experienced investors.

6. Concluding Remarks

The investment games used in these experiments were very simple. The investors did not have to estimate the current and/or future value of the asset, they had a very simple stochastic process that governed the future cash flows, and they had either two or three periods with no discounting. The subjects who participated in these experiments are believed to have no theoretical or practical training in real options. One conclusion to be drawn from the timing of investment sessions is that even for simple investment projects the timing arguments of the real options theory vis-à-vis the NPV approach are not very obvious and intuitive to investors who are not trained or educated on this topic. Perhaps this should not be surprising. For years, even expert economists and financial analysts believed that oil companies were paying too much for offshore oil drilling rights, because their assessments were based on the NPV approach and failed to incorporate the value of the flexibility with respect to the timing of the drills.

It is interesting, however, that the subjects' bidding behavior on two more challenging aspects of the option theory were generally close to the predicted outcome. The winning bids were very close to the levels expected by the theory and the bids increased with the uncertainty about the future cash flows. These are more challenging aspects of the theory because the bids should

incorporate the value of the timing flexibility embedded in the project. So, how did the subjects discover the theoretical bid levels yet failed to exercise optimal timing? One possible explanation is that timing decisions are “individual” decisions whereas the winning bid is determined by an auction/competition among all the players. While at the individual level majority of the investors may fail to recognize the value of the real option, competition among the investors in the market drives the asset prices to levels that reflect the option values.

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Appendix

Instructions for Session T1

General Rules

This is an experiment in investment decision making. If you follow the instructions carefully and make good decisions, you can earn a considerable amount of money. You will be paid in private and in cash at the end of the experiment.

It is important that you do not talk to one another until the experiment is over. If at any time during the experiment you have questions or problems, raise your hand and one of the monitors will assist you. The experiment will consist of 18 rounds. The first 3 rounds will be practice rounds. The purpose of the practice rounds is to familiarize you with the experimental procedures. Nothing that you do in the practice rounds will affect your earnings.

The rules for each round are identical. In each round you will have a chance to earn some points. How many points you earn will depend on your investment decisions in that round. At the end of the experiment one of rounds 4 to 18 will be randomly selected and you will receive $1.00 for every 1,000 points you earned in that round. The more points you earn, the greater your earnings will be. It is in your interest to make as many points as you can in each and every round. You will start the experiment with an initial balance of $10.00.

The Investment Project

Each round is divided into 3 investment periods. Each round, you will decide whether to invest in a project in the first, second, or the third period of that round.

If you decide to invest in a round, regardless of which period of the round you invest, it will cost you 25,000 points to invest in the project.

The investment project generates 2,500 points in the first period. In the second period, the project will generate either 22,500 points or 7,500 points, each with equal probability. Whether the income for the second period is 22,500 or 7,500 points will be determined by the roll of a dice by one of the participants at the end of the first period. If the dice comes out as an even number (2, 4 or 6) the income for the second period will be 22,500 points, and if it comes out as an odd number (1, 3 or 5), the income will be 7,500 points. In the third period, the project will generate either 45,000 points, or 15,000 points or 0 points, depending on the outcome of a new dice roll at the end of the second period and the outcome of the previous dice roll at the end of the first period. If the first and second dice rolls both come out as an even number, then the income in the third period will be 45,000 points. If the first dice roll was an odd number and second dice roll comes out as an even number, then the income in the third period will be 15,000 points. If the second dice roll comes out as an odd number, then the income in the third period will be 0 points regardless of the outcome of the first

dice roll. There is no resale value of this investment.

Therefore, your choices in a round are as follow:

1. Invest in period 1, without knowing the income for periods 2 and 3, and possibly earn income in all three periods, or
2. Give up the first period's income and wait until the first dice roll, find out what the income for period 2 will be, then decide whether or not to invest. If you invest in round 2 (after the first dice roll), then you will earn the amount for round 2 indicated by the first dice roll and the as yet unknown payoff from round 3 that will be determined by the next dice roll.
3. Give up the first two periods' income and wait until the second dice roll, find out what the income for period 3 will be, and then decide whether or not to invest.

Description of Each Round

Each round consists of 3 two-minute periods. A monitor will keep the time and announce the end of each period. Each round involves the following simple steps:

$ 1. You decide whether or not to invest in the project in period 1. You record your decision for period 1 by circling the appropriate box on the "Decision Form" in front of you with a pen. Once you have circled your decision, you cannot change it.

$ 2. After two minutes, a monitor will announce that period 1 has ended and one of you will be asked to roll the dice to determine the income from the project in period 2. We then go to period 2. If you had chosen not to invest in period 1, you will make a decision whether or not to invest in period 2 after having observed the outcome of the first dice roll. You will record your choice for period 2 on the Decision Form.

- 3. After two minutes, a monitor will announce that period 2 has ended and one of you will be chosen again to roll the dice to determine the income from the project in period 3. We then go to period 3. If you had chosen not to invest in periods 1 or 2, you will make a decision whether or not to invest in period 3 after having observed the outcome of the second dice roll. You will record your choice for period 3 on the Decision Form.

$ 4. At the end of period 3, you calculate your point earnings for that round and record them on the Earnings column of the Decision Form in front of you. A monitor will check your calculations and, after everyone has entered their earnings for the round correctly, the next round will begin.

If you do not make a decision within two minutes in any period, this will be treated as a decision not to invest in that period.

How your earnings are determined

Your point earnings or losses in a round will be determined by which period you choose to invest and the outcome of the dice rolls. Recall that if you invest in any of the periods of a round, an investment cost of 25,000 points will be deducted from your earnings in that round.

If you invest in period 1 of a round: You will receive 2,500 points for period 1, plus, depending on the outcome of the two dice rolls, either 22,500 points or 7,500 points for period 2, and 45,000 points or 15,000 points or 0 points for period 3, minus the investment cost. More specifically, you will earn 2,500 + 22,500 + 45,000 - 25,000 = 45,000 points if both dice rolls come out as an even number, you will earn 2,500 + 22,500 - 25,000 = 0 points if the first dice roll comes out as an even number and the second one comes out as an odd number, you will earn 2,500 + 7,500 + 15,000 - 25,000 = 0 points if the first dice roll comes out as an odd number and the second one comes out as an even number, and you will lose 2,500 + 7,500 - 25,000 = -15,000 points if both dice rolls come out as an odd number.

If you invest in period 2 of a round: Since the first dice is rolled at the end of period 1, you would know the outcome of the first dice roll before you decide whether to invest in period 2. If you invest after the first dice roll came out as an even number, you will have an income of 22,500 points in period 2 plus either 45,000 points or 0 points for period 3, depending on the outcome of the second dice rolls. More specifically, you will earn 22,500 + 45,000 - 25,000 = 42,500 points if the second dice roll is an even number and lose 22,500 + 0 - 25,000 = -2,500 points if the second dice roll is an odd number. If you invest after the first dice roll came out as an odd number, you will have an income of 7,500 points in period 2 plus either 15,000 points or 0 points for period 3, depending on the outcome of the second dice rolls. More specifically, you will lose 7,500 + 15,000 - 25,000 = -2,500 points if the second dice roll is an even number and lose 7,500 + 0 - 25,000 = -17,500 points if the second dice roll is an odd number.

If you invest in period 3 of a round: Since the second dice is rolled at the end of period 2, you will know the outcome of the both dice rolls before you decide whether to invest in period 3. If you invest after both dice rolls came out as an even number, you will have a profit of 45,000 - 25,000 = 20,000 points. If you invest after the first dice roll came out as an odd number and the second dice roll came out as an even number, then you will have a loss of 15,000 - 25,000 = -10,000 points for that round. If you invest after the second dice roll came out as an odd number, then regardless of the outcome of the first dice roll you will have a loss of -25,000 points.

The following table summarizes earnings / losses from the three choices under different outcomes of the two dice rolls:

If you Invest in Outcome of the	**Period 1 (no dice roll**	**Period 2 (1st dice roll**	**Period 3 (both dice rolls**

Two Dice Rolls (E=Even, O=Odd)	**observed)**	**observed)**	**observed)**
E & E	45,000	42,500	20,000
E & O	0	-2,500	-25,000
O & E	0	-2,500	-10,000
O & O	-15,000	-17,500	-25,000

If you decide not to invest at all in a round, you will have zero earnings or loss for that round.

You start the experiment with an initial credit of $10.00 (=10,000 points). At the end of the experiment one of rounds 4 to 18 will be randomly selected and you will receive/lose $1.00 for every 1,000 points you earned/lost in that round. Each of you will select this round individually. In order to select this round, a monitor will come around and ask you to draw a card from a deck of cards numbered 4-18. Your earnings (or losses) from that round will be added to (or subtracted from) your initial credit of $10.00.

Are there any questions?

Instructions for Session B1

General Rules

This is an experiment in investment decision making. If you follow the instructions carefully and make good decisions, you can earn a considerable amount of money. You will be paid in private and in cash at the end of the experiment.

It is important that you do not talk to one another until the experiment is over. If at any time during the experiment you have questions or problems, raise your hand and one of the monitors will assist you. The experiment will consist of 18 rounds. The first 3 rounds will be practice rounds. The purpose of the practice rounds is to familiarize you with the experimental procedures. Nothing that you do in the practice rounds will affect your earnings.

The rules for each round are identical. In each round you will have a chance to earn some points. How many points you earn will depend on your investment decisions in that round. In each round, you will make a bid to have the right to participate in an investment project. You will submit your bids to a monitor using the bidding forms provided. Once everyone submits his/her bid, we will rank the bids from the highest to the lowest. The top 10 bidders (those who submit one of the highest 10 bids) will earn the right to participate in the investment project. Each of the top 10 bidders will pay the 10^{th} highest bid. If you are one of the top ten bidders in a round, your earnings then will be equal to your earnings from the investment project in that round minus the 10^{th} highest bid that you have to pay. If you are not one of the top ten bidders in a round, your earnings will simply be equal to zero

for that round. If there is a tie between two or more of you for the 10^{th} spot, we will randomly draw from among the bidding forms that tied for the 10^{th} spot.

At the end of the experiment one of rounds 4 to 18 will be randomly selected and you will receive $1.00 for every 1,000 points you earned in that round. The more points you earn, the greater your earnings will be. It is in your interest to make as many points as you can in each and every round. You will start the experiment with an initial balance of $15.00.

The investment project that you will be bidding for is described below.

The Investment Project

Following the bidding process, there will be 2 investment periods in each round. If you win the right to participate in the investment project, you will decide whether to invest in the project in the first or the second period of that round.

If you decide to invest in a round, regardless of which period of the round you invest, it will cost you 25,000 points to invest in the project.

The investment project generates 2,500 points in the first period. In the second period, the project will generate either 45,000 points or 15,000 points, each with equal probability. Whether the income for the second period is 45,000 or 15,000 points will be determined by the roll of a dice by one of the participants at the end of the first period. If the dice comes out as an even number (2, 4 or 6) the income for the second period will be 45,000 points, and if it comes out as an odd number (1, 3 or 5), the income will be 15,000 points. There is no resale value of this investment.

Therefore, your choices in a round are as follow:

4. Invest in period 1, without knowing the income for period 2, and earn income in both periods, or
5. Give up the first period's income and wait until the dice roll, find out what the income for period 2 will be, and then decide whether or not to invest.

Description of Each Round

We start each round with the bidding process. You have 2 minutes to submit your bids. The bidding is followed by 2 two-minute investment periods. A monitor will keep the time and announce the end of each 2-minute period. Each round involves the following simple steps:

$ You decide on how much to bid (your bid can be any integer number between 0 and 40,000 points), write your bid on the bidding form provided, and submit it to a monitor. You also record your bid on the "Decision Form" in front of you with a pen. Once you record your bid, you cannot change it. Once all bids are received, the 10^{th} lowest winning bid will be announced, the bidding forms with a winning bid will be marked, and all bidding forms will be returned. If your bid is not one of the top ten bids, the round for you ends and you earn zero points in that round.

If your bid is one of the top ten bids, you then take the following steps.

$ 1. You decide whether or not to invest in the project in period 1. You record your decision for period 1 by circling the appropriate box on the "Decision Form" in front of you.

$ 2. After two minutes, a monitor will announce that period 1 has ended and one of you will be asked to roll the dice to determine the income from the project in period 2. We then go to period 2.

$ 3. If you had chosen not to invest in period 1, you will make a decision whether or not to invest in period 2 after having observed the outcome of the dice roll. You will record your choice for period 2 on the Decision Form.

$ 4. At the end of period 2, you calculate your point earnings for that round and record them on the Earnings column of the Decision Form in front of you. A monitor will check your calculations and, after everyone has entered their earnings for the round correctly, the next round will begin.

If you do not make a decision within two minutes in any period, this will be treated as a decision not to invest in that period.

How your earnings are determined

a) If you are not one of the top ten bidders in a round, your earnings will simply be equal to zero for that round.

b) If you are one of the top ten bidders in a round, your point earnings or losses for that round will be determined by which period you choose to invest, the outcome of the dice rolls, and the bid that you had to pay. Recall that if you invest in any of the periods of a round, an investment cost of 25,000 points will be deducted from your earnings in that round. After you pay the 10^{th} highest bid, your earnings or losses from the investment project will be as follows:

If you invest in period 1 of a round: You will receive 2,500 points for period 1, plus either 45,000 points or 15,000 points for period 2 depending on the outcome of the dice roll at the end of the first period, minus the investment cost, minus the 10^{th} highest bid. Let X denote this bid. More specifically, you will earn a profit of 2,500 + 45,000 - 25,000 - X = 22,500 - X points if the dice roll comes out as an even number, or lose 2,500 + 15,000 - 25,000 - X = -7,500 - X points if the dice roll comes out as an odd number.

If you invest in period 2 of a round: Since the dice is rolled at the end of period 1, you will know the outcome of the dice roll before you decide whether to invest in period 2. If you invest after the dice roll came out as an even number, you will have a profit of 45,000 - 25,000 - X = 20,000 - X points. If you invest after the dice roll came out as an odd number, you will have a loss of 15,000 - 25,000 - X = -10,000 - X points.

The following table summarizes earnings / losses from the two choices under different outcomes of the dice roll:

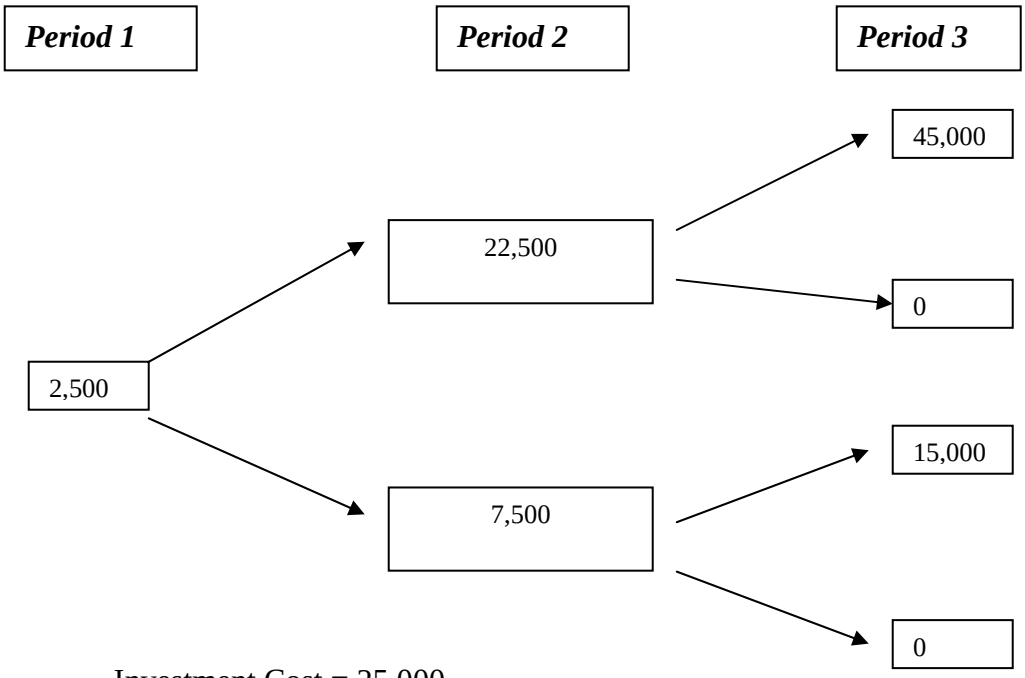
If you Invest in Outcome of the Dice Roll	**Period 1 (dice roll not observed)**	**Period 2 (dice roll observed)**
Even	22,500 - X	20,000 - X
Odd	-7,500 - X	-10,000 - X

If you decide not to invest during a round, you will have zero earnings or loss from the investment, thus your loss for that round will be equal to the bid that you had to pay.

You start the experiment with an initial credit of $15.00 (=15,000 points). At the end of the experiment one of rounds 4 to 18 will be randomly selected and you will receive/lose $1.00 for every 1,000 points you earned/lost in that round. Each of you will select this round individually. In order to select this round, a monitor will come around and ask you to draw a card from a deck of cards numbered 4-18. Your earnings (or losses) from that round will be added to (or subtracted from) your initial credit of $15.00.

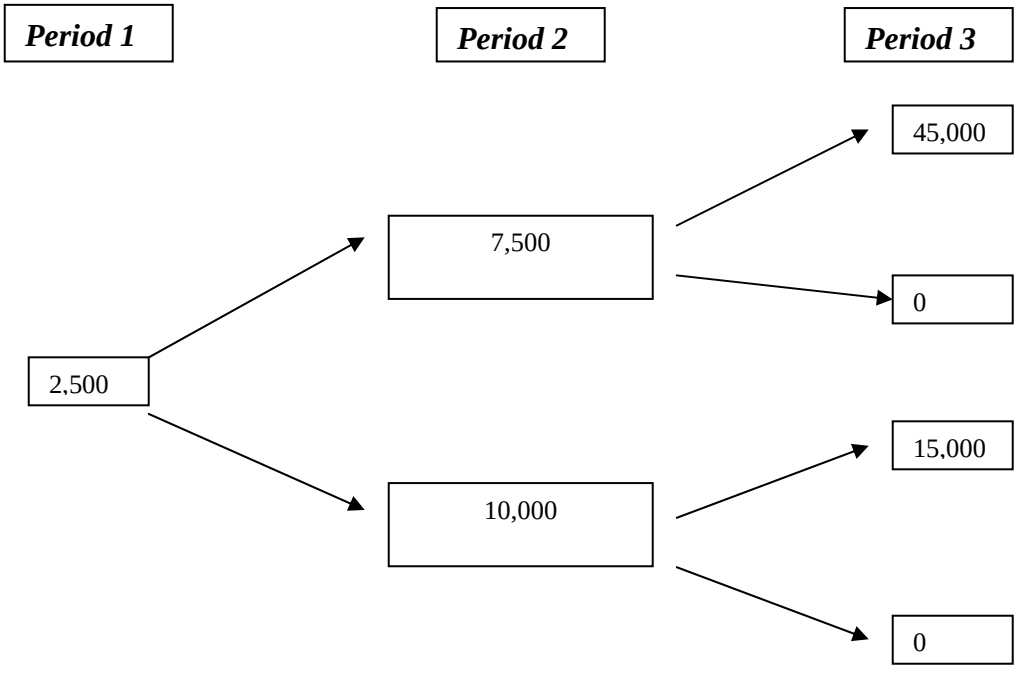
Are there any questions?

Figure 1a: Timing of the Investment (Game T1)



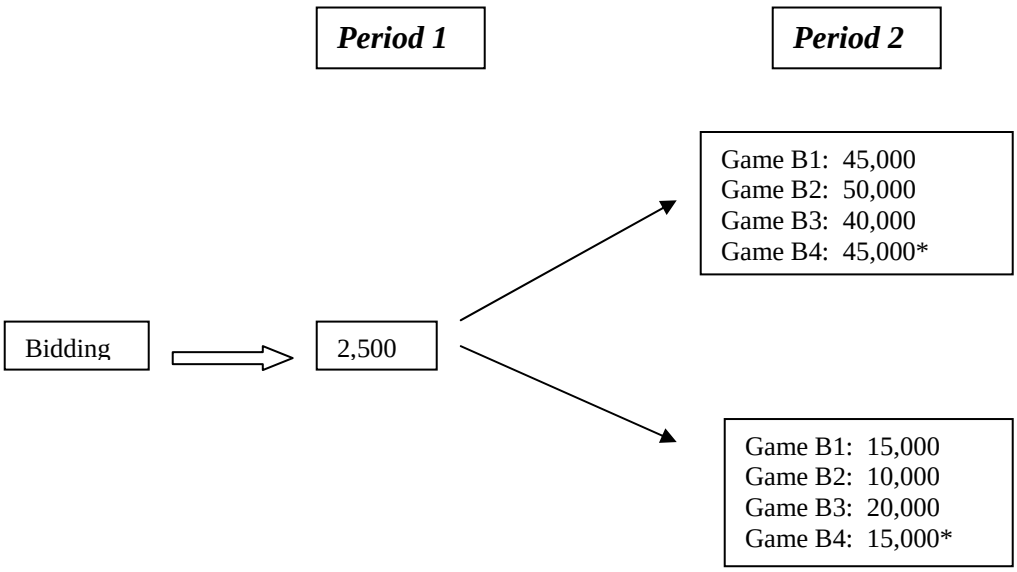
Investment Cost = 25,000

Figure 1b: Timing of the Investment (Game T2)



Investment Cost = 25,000

Figure 2: Real Option Premium and Its Correlation with Uncertainty of Future Cash Flows



Investment Cost = 25,000

* Game B4 differed from Game B1in that the investors in Game B4 did not have the option of delaying the investment until the second period.

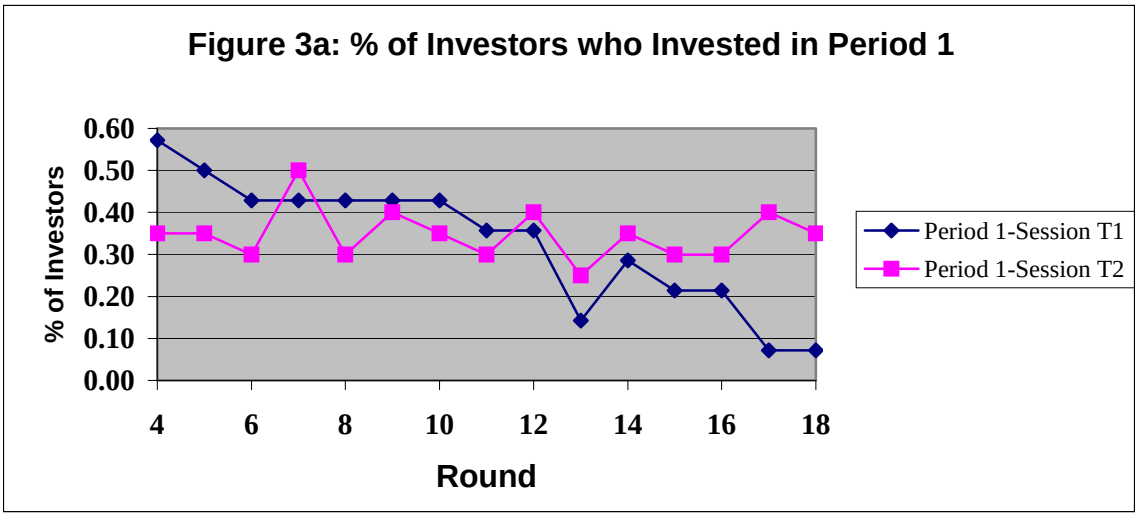


Figure 3a: % of Investors who Invested in Period 1
% of Investors
0.60
0.50
0.40
0.30
0.20
0.10
0.00
4
6
8
10
12
14
16
18
Round
Period 1-Session T1
Period 1-Session T2

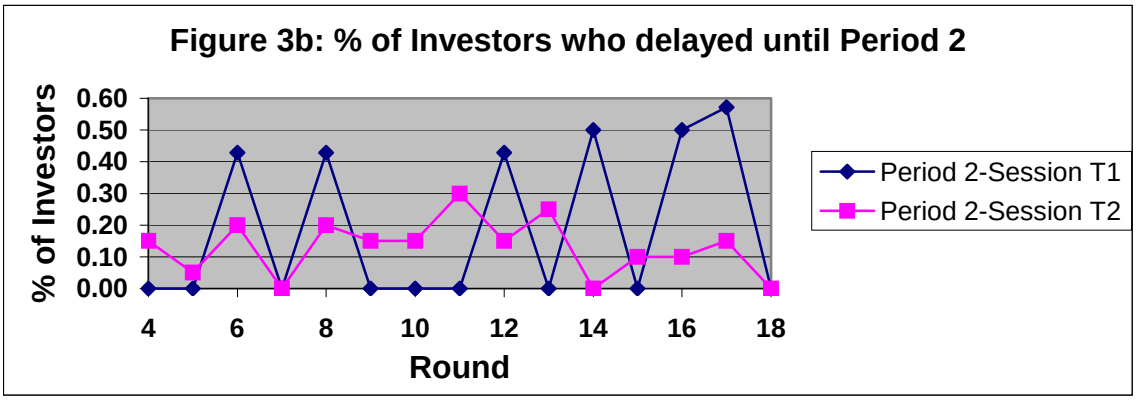


Figure 3b: % of Investors who delayed until Period 2
% of Investors
0.60
0.50
0.40
0.30
0.20
0.10
0.00
4
6
8
10
12
14
16
18
Round
Period 2-Session T1
Period 2-Session T2

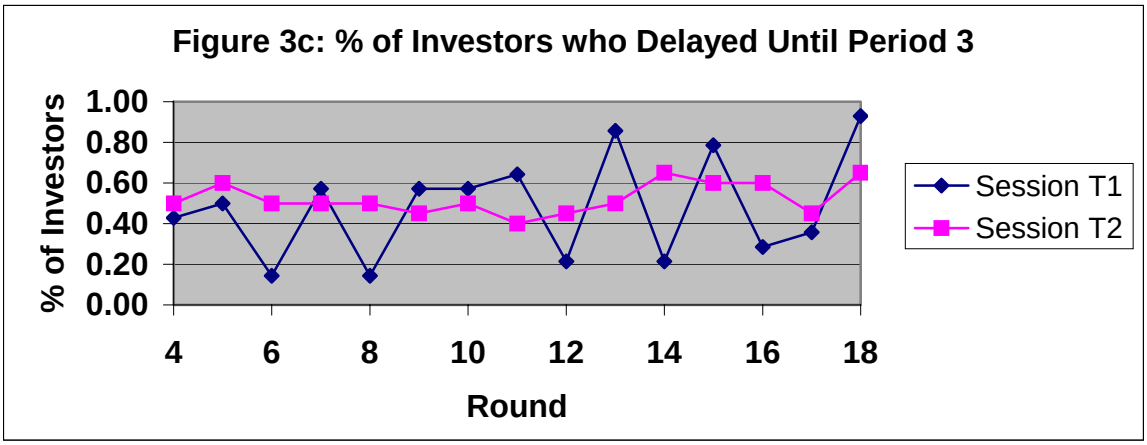


Figure 3c: % of Investors who Delayed Until Period 3
% of Investors
1.00
0.80
0.60
0.40
0.20
0.00
4
6
8
10
12
14
16
18
Round
Session T1
Session T2

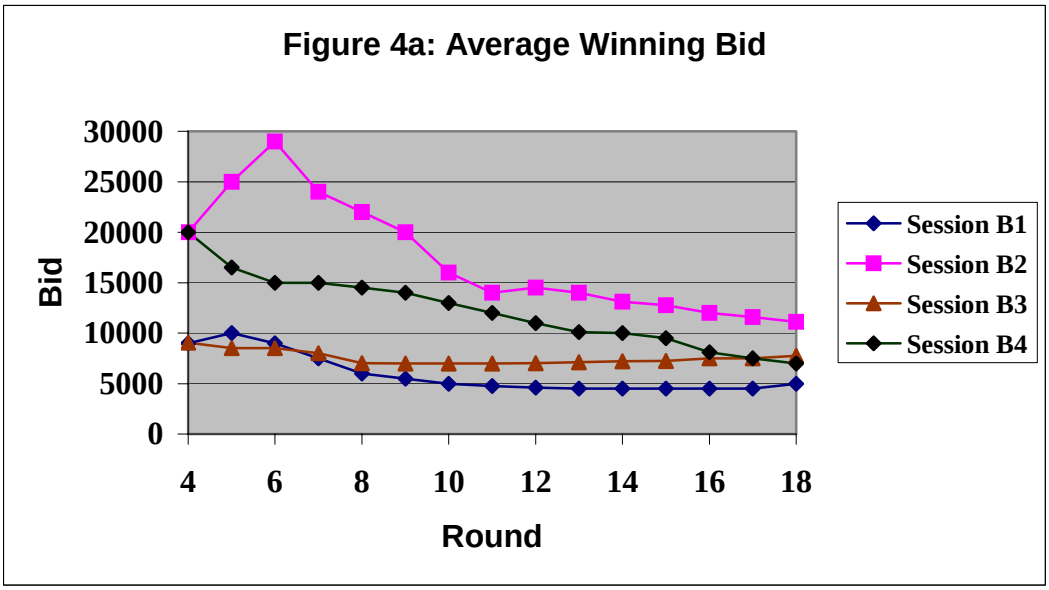


Figure 4a: Average Winning Bid
30000
25000
20000
15000
10000
5000
0
Bid
4
6
8
10
12
14
16
18
Round
Session B1
Session B2
Session B3
Session B4

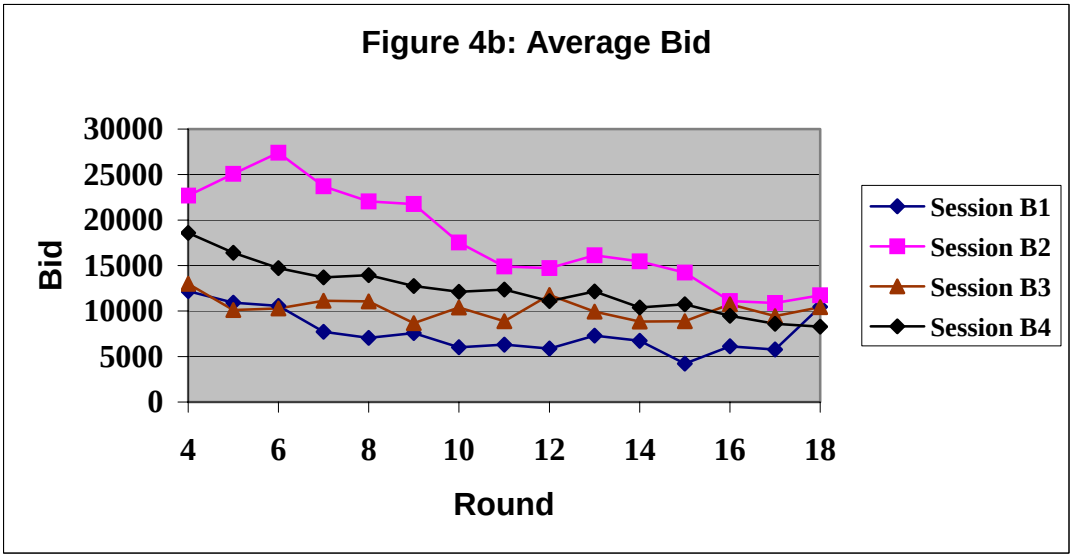


Figure 4b: Average Bid
30000
25000
20000
15000
10000
5000
0
Bid
4
6
8
10
12
14
16
18
Round
Session B1
Session B2
Session B3
Session B4