# Effects of Ambiguity in Market Experiments

Rakesh K. Sarin • Martin Weber
*Anderson Graduate School of Management, University of California Los Angeles, Los Angeles, California* 90024
*Institut für Betriebswirtschaftslehre, Universität Kiel, D-*2300 *Kiel, Germany*

Prior studies have shown that individuals are averse to ambiguity in probability. Many decisions are, however, made in market settings where an individual's decision is influenced by decisions of others participating in the market. In this paper, we extend the previous research to evaluate the effect of ambiguity on individual decisions and the resulting market price in market settings. We therefore examine an important issue: whether ambiguity effects persist in the face of market incentives and feedback.

Two different market organizations, the sealed bid auction and the double oral auction, were employed. The subjects in the experiments were graduate business students and bank executives. Our results show that the individual bids and market prices for lotteries with ambiguous probabilities are consistently lower than the corresponding bids and market prices for *equivalent* lotteries with well-defined probabilities. The aversion to ambiguity therefore does not vanish in market settings.

Our results provide insights into what a manager can expect in bidding situations where the object of the sale (oil leases, mineral rights) involves ambiguity in probability due to, for example, lack of information or prior experience. The results may also be useful in understanding some phenomena in insurance and equity markets.
(*Decisions under Uncertainty; Experimental Economics; Ambiguity*)

## 1. Introduction

Federal offshore oil land tracts are auctioned using sealed bids. The highest bidder wins the contract provided that the government's reservation price is exceeded. Some tracts are located in previously untested areas (e.g., the Baltimore Canyon sale of August 1976), whereas the others (e.g., the Texas Gulf sale of May 1974) are located in a region where the bidders have had prior experience (see Gilley et al. 1986). It is reasonable to assume that the probability associated with the event that a specified amount of oil will be found in a tract located in the untested area is vague or ambiguous. Does this vagueness influence an individual company's bids and the resulting price at which the tract is sold? If the vagueness in probability does indeed influence the bids, then the models of bidding, about a dozen of which have appeared in *Management Science*, need to be extended to account for this phenomenon. (See for example, Engelbrecht-Wiggans et al. 1986, Engelbrecht-Wiggans 1987, Hausch 1986, Lee 1984, Rothkopf et al. 1986, and Samuelson 1986; for surveys see Stark and Rothkopf 1979 and Engelbrecht-Wiggans 1980.)

Effects of ambiguity in probability on individual decisions have been demonstrated in several previous studies (e.g., see Einhorn and Hogarth 1985). A key issue is whether ambiguity effects persist in the face of market incentives and feedback. Our results reported here show that they do. An implication of these results, therefore, is that theories of market bidding processes need to address these effects. Our results could also provide insights into managerial decisions associated with specialized markets such as insurance.

Since the isolation of the impact of ambiguity on individual bids in real auctions is difficult because of the presence of several other pertinent factors, we examined


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this issue in an experimental market setting. Below we illustrate precisely the effect of ambiguity on individual decisions using Ellsberg's (1961) example.

Consider the two pairwise choice problems given below. A subject chooses between Acts 1 and 2 in Problem 1, and between Acts 3 and 4 in Problem 2. Columns represent states of the world. A state of the world (Red, Black, or Yellow) is said to occur if the respective color ball is drawn from an urn containing 30 red balls and 60 (black and yellow) balls, the latter in unknown proportion.

| | | 30 | 60 | |
|---|---|---|---|---|
| | | Red | Black | Yellow |
| Problem 1 | Act 1 | 100 | 0 | 0 |
| | Act 2 | 0 | 100 | 0 |
| Problem 2 | Act 3 | 100 | 0 | 100 |
| | Act 4 | 0 | 100 | 100 |

A majority of subjects in our experiments and in those of numerous other researchers has indicated a preference for Act 1 over Act 2 and Act 4 over Act 3. If subjects are subjective expected utility maximizers, then such a preference pattern will imply $p(R) > p(B)$, and $p(B) > p(R)$ where $p(R)$ and $p(B)$ are the probabilities of drawing a red ball and black ball respectively—a result clearly inconsistent with the theory. It has been argued in the literature that a rational decision maker should be indifferent between Acts 1 and 2 (and Acts 3 and 4) because the mean probability of receiving a payoff of 100 is identical for the two acts in both problems.

The theory of choice under uncertainty (Savage 1954) requires two uncertain options to be equivalent if both yield the identical probability distribution over payoffs (consequences, outcomes). This widely accepted theory assumes that a rational decision maker will make no distinction between the case when the probability associated with a payoff is ambiguous (vague, volatile, or shaky) and when it is precise, so long as the mean probability is identical in both cases. Ellsberg (1961) presented some ingenious examples to demonstrate that people often exhibit a preference for specificity in probabilities and seem to avoid ambiguous probabilities. Subsequently, a large literature (Becker and Brownson 1964, Smith 1969, Einhorn and Hogarth 1985, Hogarth and Kunreuther 1985, Curley and Yates 1985, Kahn and Sarin 1988, Fishburn 1988, Hogarth and Einhorn 1990, Camerer and Weber 1993) has emerged that has verified and extended Ellsberg's findings to a variety of decision situations. The key conclusion from these studies is that choices of individuals are often inconsistent with the predictions of the theory of choice under uncertainty.

In a large number of economic and financial settings, individuals do not make choices in isolation. In market settings people learn from each others' actions and have an opportunity to "correct" their decisions over time. It is quite conceivable, therefore, that the theory of choice under uncertainty could provide accurate predictions of individual choices and the resulting market price in spite of the contrary evidence at the individual level (see Friedman 1953; Blaug 1980, 110–114; and Camerer 1987 for further discussion of this issue). The purpose of this study was to examine this hypothesis in an experimental market setting.

The general approach in our experiments was to observe the individual bids and the market price of an unambiguous asset ($p_u$) and of an ambiguous asset ($p_a$) in a specified market experiment. The mean probability of receiving a payoff was controlled to be identical for the two types of assets. Since the payoffs were fixed at the same level for both the ambiguous and unambiguous assets, a rational decision maker would treat them equivalently. Loosely speaking, two identical goods must have equal market prices.

In addition, we ought to also have observed that the bid of individual $i$ for the unambiguous asset $p_u^i$ was equal to the bid for the ambiguous asset $p_a^i$. Thus, in a market setting:

$$p_u = p_a \quad \text{and} \quad p_u^i = p_a^i. \tag{1}$$

Our objective in the series of experiments reported in the following sections was to examine whether observed market prices and individual bids on the average satisfy the equality (1).

## 2. Experimental Design

### A. Objectives

We conducted three studies involving 14 experiments to test the effect of ambiguity on market prices. Experiments 1–8 constituted a single $2 \times 2 \times 2$ design and subject population; experiments 9–10 constituted a second 2-factor design; and experiments 11–14 constituted the third study, a 2 × 2 design. The objective in the first eight experiments was to test whether the individual bids and market prices of ambiguous and unambiguous assets differ in sealed-bid and double-oral auctions. The sealed bid auctions were run for eight periods and the double oral auctions were run for two periods where each period consisted of four or eight minutes of trading. In experiments 9 and 10, we examined whether the results would be sustained if experienced executives participated in the market experiment. In these experiments, we employed only sealed-bid auctions. In experiments 11–14, our objective was to test whether our results are robust to a larger number of trading periods. In these experiments sealed bid auctions were run for 16 periods and double-oral auctions were run for eight periods.

## B. Subjects

The participants in the first eight experiments were graduate students of business administration at Aachen University in Germany. They were divided into four groups of eight students each. Two groups participated in sealed-bid auctions and two in double oral auctions. Thus, each experimental market consisted of eight participants—a number considered reasonable for such experiments (see Smith 1982). In addition, we created markets using eight executives of J. P. Morgan in Frankfurt, who were bond or currency traders or advisors and had a minimum of two years of work experience (experiments 9 and 10). In experiments 11–14, the subjects were graduate students of business administration at Cologne University. All of our student subjects had taken basic economics and statistics courses but had no prior experience with experimental markets. In order to ensure that they clearly understood the rules of the auction market, a trial run for four periods was carried out for sealed-bid auctions and for one four minute period for double-oral auctions. Subjects were actually paid a specified fraction (discussed later) of their accumulated earnings at the end of the experiment; however, they were informed about the rules of payment at the beginning of the experiment. The actual earnings of the

**Table 1 A Summary of Experimental Design***

| Experiment | Group | Market Auction |
|---|---|---|
| 1 | **Aachen 1 | Sealed bid independent auction for 8 periods, $p = 0.5$ |
| 2 | Aachen 1 | Sealed bid independent auction for 8 periods, $p = 0.05$ |
| 3 | Aachen 2 | Sealed bid simultaneous auction for 8 periods, $p = 0.5$ |
| 4 | Aachen 2 | Sealed bid simultaneous auction for 8 periods, $p = 0.05$ |
| 5 | Aachen 3 | Double-oral independent auction for 2 periods, $p = 0.5$ |
| 6 | Aachen 3 | Double-oral independent auction for 2 periods, $p = 0.05$ |
| 7 | Aachen 4 | Double-oral simultaneous auction for 2 periods, $p = 0.5$ |
| 8 | Aachen 4 | Double-oral simultaneous auction for 2 periods, $p = 0.05$ |
| 9 | Executives | Sealed bid independent auction for 3 periods, $p = 0.5$ |
| 10 | Executives | Sealed bid independent auction for 3 periods, expert case, $p = 0.5$ |
| 11 | Köln 1 | Sealed bid independent auction for 16 periods, $p = 0.5$ |
| 12 | Köln 2 | Sealed bid simultaneous auction for 16 periods, $p = 0.5$ |
| 13 | Köln 3 | Double-oral independent auction for 8 periods, $p = 0.5$ |
| 14 | Köln 4 | Double-oral simultaneous auction for 8 periods, $p = 0.5$ |

* In all experiments, each unit yields a dividend of DM 100 or DM 0. The $p$-value refers to the probability of receiving DM 100 in a given experiment. In experiments 9 and 10, trades take place in blocks of 100 units.

** The order of market auctions for Aachen 1 and 3 was unambiguous, $p = 0.5$, ambiguous, $p = 0.05$, unambiguous, $p = 0.05$, and ambiguous, $p = 0.5$; for Aachen 2 and 4 it was $p = 0.5$, and $p = 0.05$; for executives it was ambiguous and then unambiguous, and for Köln 1 and 3, it was ambiguous and then unambiguous.

**Table 2 Initial Conditions and Payment Scheme**

| Experiment | Endowment: Cash | Endowment: Certificates | Resolution of Asset Value | Fixed Cost | Earnings as % of Profits |
|---|---|---|---|---|---|
| 1 | 1000 | — | periods 4, 8 | 400 | 1% |
| 2 | 1000 | — | periods 4, 8 | 400 | 1% |
| 3 | 2000 | — | periods 4, 8 | 800 | 1% |
| 4 | 2000 | — | periods 4, 8 | 800 | 1% |
| 5 | 1000/period | 2/period | each period | 1600 | 1% |
| 6 | 1000/period | 2/period | each period | 1600 | 1% |
| 7 | 2000/period | 2, 2/period | each period | 3200 | 1% |
| 8 | 2000/period | 2, 2/period | each period | 3200 | 1% |
| 9 | 50,000 | — | each period | 40,000 | 0.4% |
| 10 | 50,000 | — | each period | 40,000 | 0.4% |
| 11 | 200/2 periods | — | every other period | — | 0.6% |
| 12 | 400/2 periods | — | every other period | — | 0.6% |
| 13 | 1000/period | 2/period | each period | 800/period | 0.4% |
| 14 | 2000/period | 2, 2/period | each period | 1600/period | 0.4% |

student participants ranged between DM 11 and DM 38 and those of the executives ranged between DM 46 and DM 64 (at the time of the experiments the exchange rate was approximately one U.S. dollar to 2 DM). Each subject group participated in experiments for about two hours.

**Table 3 Market Prices of Unambiguous and Ambiguous Assets**

| Experiment | First Period: Unambiguous | First Period: Ambiguous | Last Period: Unambiguous | Last Period: Ambiguous | Averge of All Periods: Unambiguous | Averge of All Periods: Ambiguous | Number of Periods in Which Average Price of Ambiguous Asset < Average Price of Unambiguous Asset |
|---|---|---|---|---|---|---|---|
| 1 | 50 | 10 | 60 | 50 | 57.5 | 23.8 | 8 of 8 |
| 2 | 5 | 10 | 2 | 5 | 3.6 | 5.4 | 1 of 8 |
| 3 | 50 | 10 | 75 | 20 | 63.3 | 18.1 | 8 of 8 |
| 4 | 5 | 8 | 5 | 5 | 5.6 | 6.6 | 0 of 8 |
| *5 | 95 | 50 | 85 | 55 | 90 | 52.5 | 2 of 2 |
| 6 | 0.7 | 2 | 1 | 0.6 | 0.9 | 1.3 | 1 of 2 |
| 7 | 82.5 | 37.5 | 61 | 39.8 | 71.8 | 38.6 | 2 of 2 |
| 8 | 3.4 | 2.3 | 5.4 | 4.9 | 4.4 | 3.6 | 2 of 2 |
| **9 | 3033 | 3000 | 4000 | 3000 | 3577 | 3000 | 3 of 3 |
| **10 | 3033 | 1500 | 4000 | 2000 | 3577 | 1633 | 3 of 3 |
| 11 | 50.5 | 35 | 54 | 45 | 51.3 | 39.8 | 16 of 16 |
| 12 | 50 | 25 | 50.5 | 28 | 50 | 28.6 | 16 of 16 |
| 13 | 62.5 | 40 | 60 | 60 | 62.8 | 55.8 | 5 of 8 |
| 14 | 140 | 35 | 78 | 59.5 | 96.6 | 47.5 | 8 of 8 |

* In double oral auctions last four contract prices in each period are averaged. In our experiments prices exhibit convergence in last four to eight contracts.

** The executive subjects traded in blocks of 100 certificates each.

**Table 4 Distribution of Units Among Traders at End of Auction (unambiguous, ambiguous)**

| | Trader Number | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Experiment | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | 4, 2 | 5, 0 | 4, 1 | 5, 5 | 4, 5 | 3, 6 | 7, 8 | 0, 5 |
| 2 | 3, 4 | 3, 4 | 1, 2 | 4, 8 | 5, 5 | 8, 7 | 4, 0 | 4, 2 |
| 3 | 2, 3 | 8, 5 | 2, 6 | 6, 3 | 2, 6 | 8, 3 | 4, 5 | 0, 1 |
| 4 | 3, 2 | 2, 3 | 3, 3 | 8, 8 | 8, 7 | 2, 2 | 4, 6 | 2, 1 |
| 5 | −2, −5 | 4, −1 | 12, 12 | 3, −12 | 4, 5 | 5, 6 | 4, 1 | 2, 26 |
| 6 | 19, 16 | −11, −4 | 6, 16 | −3, 3 | 13, 2 | 4, 5 | 1, 6 | 3, −12 |
| 7 | 9, 16 | 9, 1 | 7, 0 | 1, 0 | 5, 5 | 0, 5 | 1, −1 | 0, 6 |
| 8 | 5, 3 | 8, 4 | 7, 4 | 5, 6 | 5, 4 | 6, 6 | 5, 2 | −9, 3 |
| 9 | 1, 1 | 2, 0 | 1, 1 | 1, 3 | 1, 2 | 2, 1 | 2, 2 | 2, 2 |
| 10 | 1, 0 | 2, 2 | 1, 1 | 1, 1 | 1, 2 | 2, 1 | 2, 2 | 2, 3 |
| 11 | 14, 10 | 4, 5 | 1, 1 | 7, 12 | 4, 14 | 13, 9 | 12, 7 | 9, 6 |
| 12 | 11, 3 | 0, 16 | 9, 1 | 9, 9 | 7, 16 | 7, 3 | 11, 8 | 10, 8 |
| 13 | −5, −3 | 6, 6 | 60, 50 | 10, 8 | 75, 12 | −57, 21 | 24, 23 | 13, 11 |
| 14 | 9, 19 | 16, 20 | −9, −8 | 5, 13 | 29, 30 | 34, 19 | 1, 33 | 43, 2 |

## C. Operationalization of Ambiguity

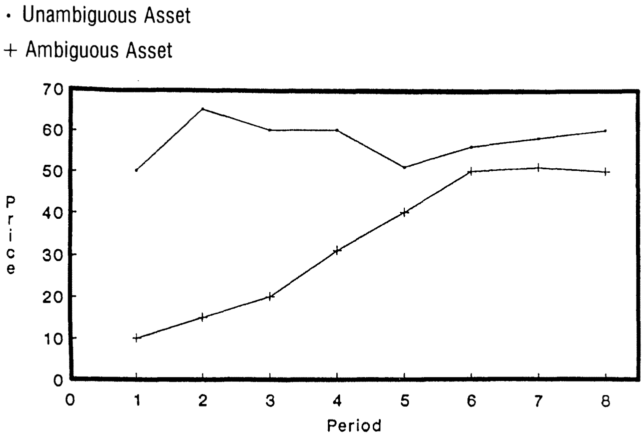
The objects of the trade in our experiments were two types of assets that paid liquidating state-dependent dividends. The first type of asset (labelled red) paid DM 100 with a $p$ chance and DM 0 with $(1 - p)$ chance. The probability in this case was unambiguous, so we call this an unambiguous asset. To operationalize $p = 0.5$, an opaque urn was filled with 10 yellow and 10 white tennis balls. A subject was randomly selected who named a color and drew one ball out of the urn. If the color of the ball drawn agreed with the color named, then the value of the asset was DM 100; otherwise it was DM 0. For $p = 0.05$, the urn was filled with 20 balls numbered 1 to 20. The subject named one number and drew a ball. If the number named agreed with the number on the ball drawn, the value of the asset was DM 100; otherwise it was DM 0.

The second type of asset (labelled green) paid DM 100 with a chance that could be anywhere between 0% and 100% but had a mean of $\bar{p}$ and paid DM 0 with a complementary chance. To operationalize $\bar{p} = 0.5$ ($p$ between 0% and 100%), an urn was filled with 20 yellow *and* white balls but the subjects did not know the proportion of yellow or white balls in the urn. Thus, the urn might have contained all white balls, all yellow balls, or a mixture of the two. The proportion of yellow and white balls was determined by using a random number table. The subjects were told about the process employed for determining the proportion of yellow and white balls. Essentially, the proportion of yellow and white balls was rearranged before each period depending on the next number in the random number table. Since the subjects were dealing with a new urn after each resolution, the degree of ambiguity was not dependent on the outcome of the previous drawing. The probability of drawing a white or yellow ball was ambiguous in this case. A subject was randomly chosen who named a color and drew a ball from the urn. If the color named agreed with the color of the ball drawn, the asset value was judged to be DM 100; otherwise it was judged to be DM 0.

Since $p$ in this case is a random variable with uniform density, a rational decision maker will act as if the probability of gaining DM 100 is simply $\bar{p}$. Since the subject is free to choose a yellow or white ball, the probability of gaining DM 100 is at least 0.5. Thus, the bid price for an ambiguous asset must be at least as much as the bid price for an unambiguous asset. This conclusion is supported by Savage (1954) and Raiffa (1961).

In addition to the process described above, in experiment 10 we employed another manipulation of ambiguity. In this manipulation the success probability was estimated by three experts. Expert 1 assessed it to be 0.1, Expert 2 assessed 0.5, and Expert 3 assessed 0.9.

**Figure 1** **Market Price for Unambiguous Asset in Sealed-Bid Auction (Independent Case, Experiment 1)**




The chance that a given expert was correct was $\frac{1}{3}$. Thus, the mean probability in this expert case was also 0.5. To operationalize the expert case, a randomly chosen subject drew a ball out of an urn containing three balls. These balls were labeled 1, 2, or 3, indicating which expert was correct. The subject in the second step drew a ball from an urn $i$ if expert $i$ was correct. Urn 1 contained two white and eighteen yellow balls, urn 2 contained ten white and ten yellow balls, and urn three contained eighteen white and two yellow balls. Thus, if Expert 3 was correct, the subject drew a ball from urn 3. The asset value was judged to be DM 100 if a white ball was drawn, and DM 0 otherwise.

We made a deliberate attempt to make the mean probability of gaining DM 100 to be transparent so that, if a subject did wish to bid based upon the mean probability alone, he could do so. For uniform distributions around 0.5, it was easy for the subjects to compute the mean probability mentally. We note that our procedure for operationalizing ambiguity may have reduced the impact of ambiguity that would otherwise have occurred if a person did not know any distribution for probability of winning (see Yates and Zukowski 1976). We deliberately chose this transparent scheme to eliminate any possibility of a subject assuming that the mean probability of winning was lower (or higher) for the ambiguous urn. In order to maintain neutral labels the assets were always referred to as red or green. Subjects never encountered "ambiguous" and "unambiguous" labels in instructions or actual trades.

## D. Market Procedure

We investigated two types of experimental markets: sealed-bid and double-oral auctions. We employed double-oral auctions because convergence to the competitive equilibrium is faster in these markets as compared with the sealed-bid auctions (see Smith et al.

**Figure 2** **Market Price for Unambiguous and Ambiguous Asset in Double-Oral Auction (Independent Case, Experiment 5)**

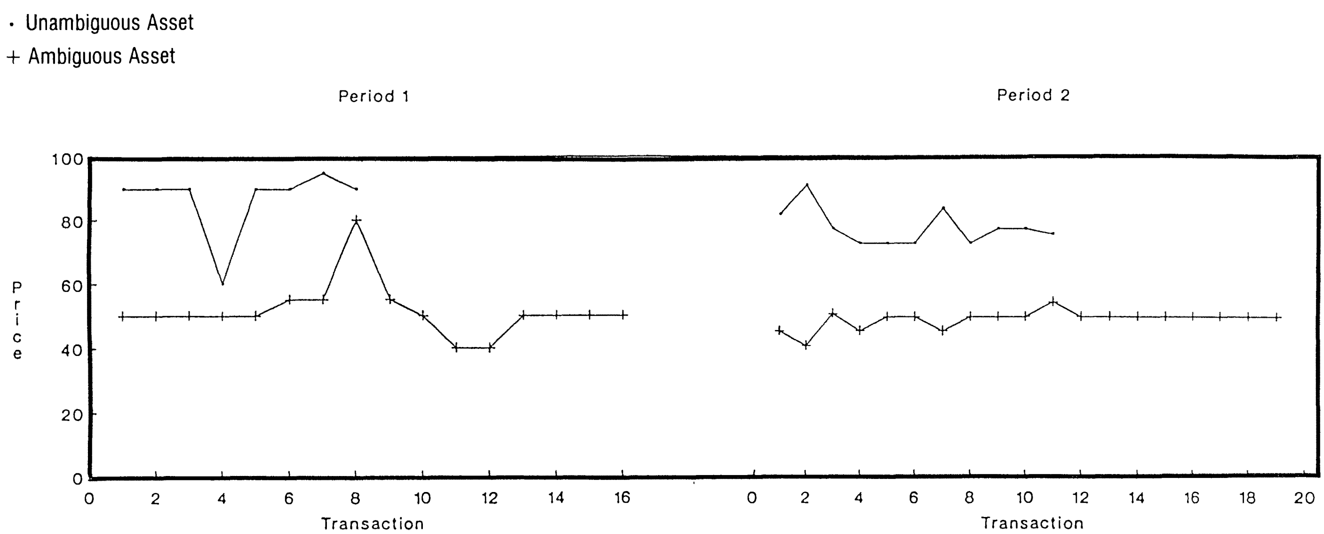
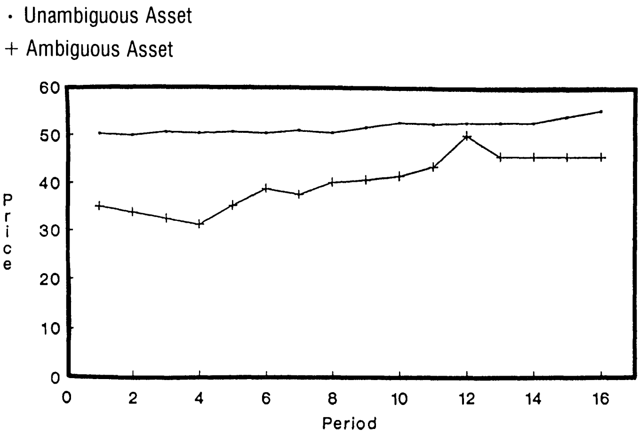


**Figure 3** **Market Price for Unambiguous and Ambiguous Asset in Sealed-Bid Auction (Independent Case, Experiment 11)**




1982). Further, a greater confidence in the results is obtained if these hold for alternative experimental markets and subject pools. In each market two types of assets (unambiguous and ambiguous described earlier) were traded *independently* as well as *simultaneously*. In independent trades, subjects sequentially traded each type of asset. The order of which asset was traded first was determined randomly for the first set of experiments. Since subjects may behave differently as they gain experience, we balanced the order of treatments for the subsequent set of experiments. Thus, for some experiments unambiguous assets were traded first and then ambiguous assets, and for the others the reverse order was employed. The exact order of auctions for our experiments is given in the footnote of Table 1. Bid

**Figure 4** **Market Price for Unambiguous and Ambiguous Asset in Double-Oral Auction (Independent Case, Experiment 13)**

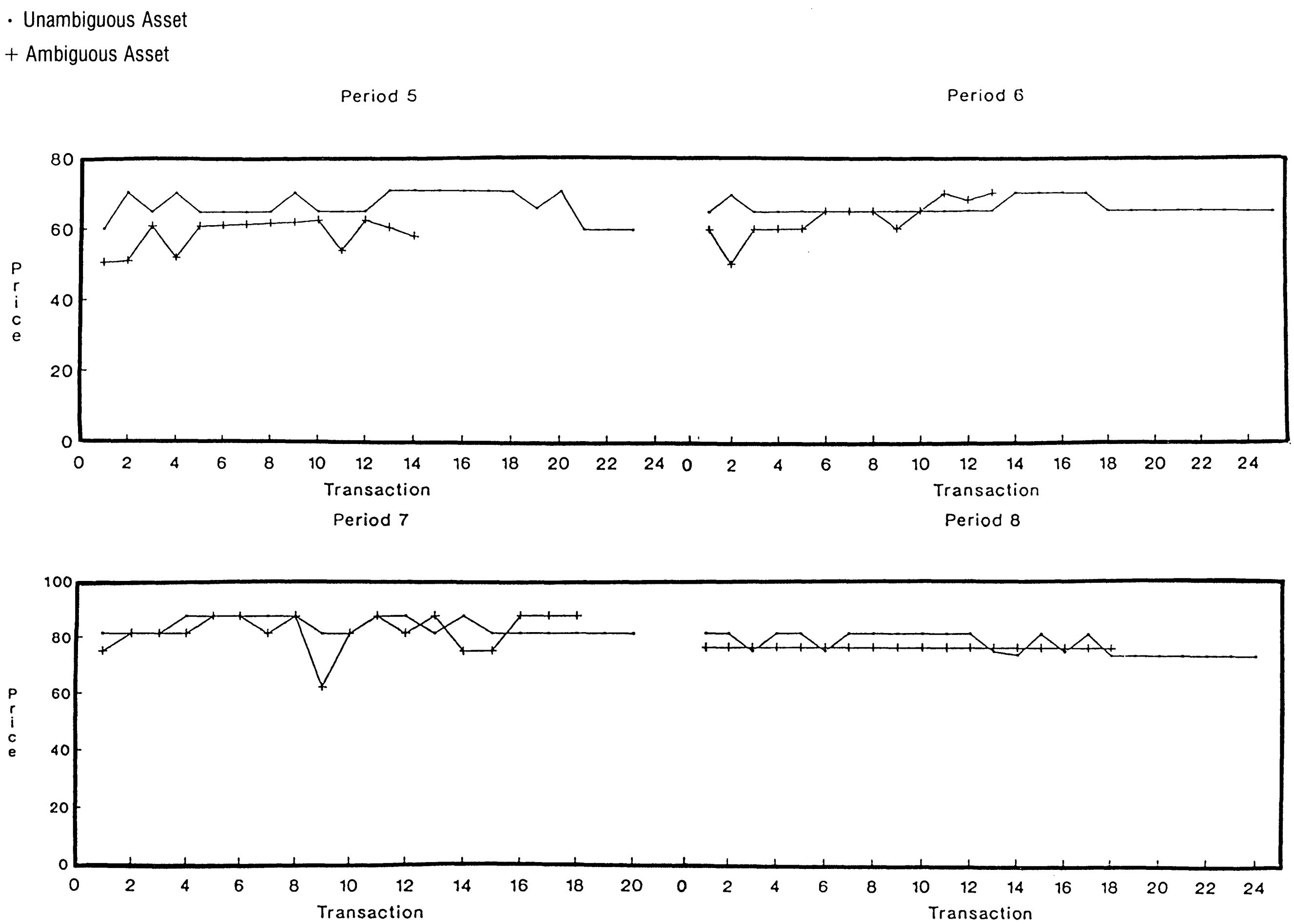
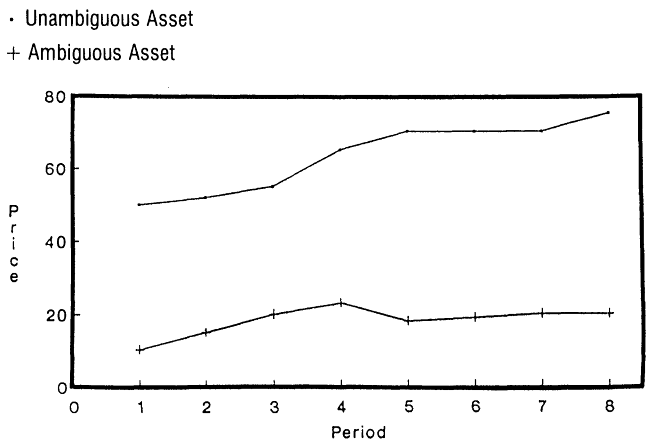


**Figure 5** **Market Price for Unambiguous and Ambiguous Asset in Sealed-Bid Auction (Simultaneous Case, Experiment 3)**




prices for the assets with ambiguous and unambiguous probabilities are often not precise in subjects' minds. Therefore, a difference in market prices may be attributed to a lack of transparent and direct comparison between two types of assets in the independent auction. To facilitate the direct comparison between the two types of assets, both assets were traded simultaneously. In Table 1, a summary of the experimental design is presented.

**Sealed-bid Auction.** In the sealed bid auctions, four certificates were sold each period. The certificates were sold to the four highest bidders at a price equal to the bid of the fifth highest bidder (see Vickrey 1961). The subjects were given instructions explaining that it was to their advantage to bid their true reservation price. Further, in order to ensure that they clearly understood the rules of the auction market, a trial run for four periods was carried out. In each experiment the subjects were told the number of periods for which the experiment would be run. The mechanics for real auctions involved each participant indicating a bid price in each period $i$. The eight bid prices from the eight participants were collected by the experimenter who posted 1 or 0 on their respective forms to indicate whether they bought a certificate or not. The fifth highest price for each bid period was written on the blackboard. This was the price that the winners actually paid. Ties among bid prices were resolved using a random number table.

Each subject was endowed with sufficient initial capital to buy more than the maximum possible number of certificates. The maximum was the number of periods in the independent case, since only one certificate could be bought in each period, or twice the number of periods in the simultaneous case. This enabled competition to

**Figure 6** **Market Price for Unambiguous and Ambiguous Asset in Double-Oral Auction (Simultaneous Case, Experiment 7)**

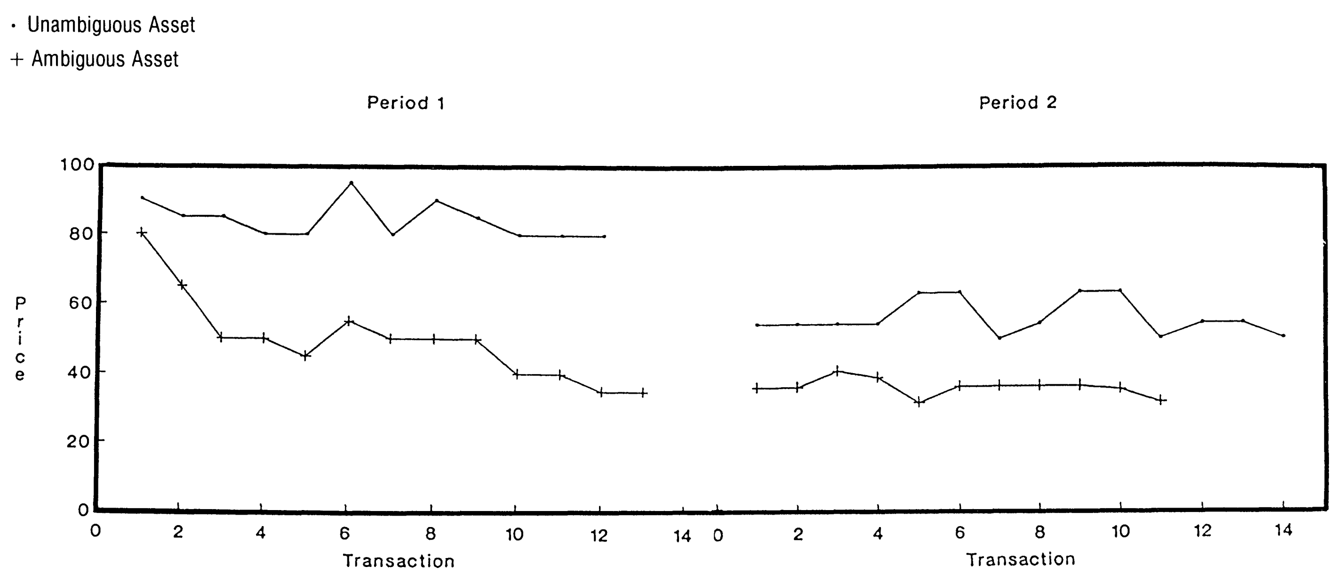
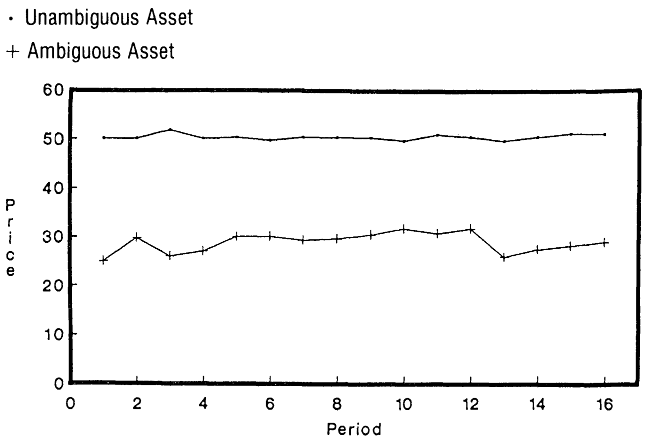


**Figure 7 Market Price for Unambiguous and Ambiguous Asset in Sealed-Bid Auction (Simultaneous Case, Experiment 12)**




drive prices to competitive equilibrium, since there was excess demand at any price less than the competitive equilibrium. The initial cash endowment for each of our experiments is given in Table 2. At the end of a specified number of periods (see Table 2) the asset value was announced, using the procedure described earlier, and participants calculated their profits. The actual amount paid to the participants is given by $\alpha$ [Profits $- F$], where $F$ is the fixed cost per experiment (tax) and $\alpha$ the fraction of the profits earned that is actually paid out. (See Table 2 for the values of the parameters used in each experiment.)

**Double-Oral Auction.** In double-oral auctions subjects are endowed with cash and certificates (two red or two green in the independent case, and two red and two green in the simultaneous case) in each period. In each experiment, a trial period is run for four minutes. Subjects are told the number of periods and the length of each period at the beginning of each experiment. Subjects made verbal bids to buy a certificate at a specified price (bid price) or sell a certificate at a specified price (offer price). Bid prices had to be higher than outstanding bids and offer prices had to be lower than outstanding offers. A matching bid and offer constituted a trade and all previous bids and offers were erased. The experimenter wrote all bids, offers and trades on a transparency visible to subjects. Once a match between a bid and an offer occurred, the contracting traders record the transaction on their information and record sheet for the current trading period. Subjects could sell certificates they did not hold (short selling). However, they had to pay the dividend value at the end of the period when the asset value was revealed. Subjects were not permitted to buy a certificate if they ran out of cash. This situation, however, did not occur in any of our experiments because of the large endowment of cash. Each trading period lasted four minutes in the independent case and eight minutes in the simultaneous case. At the end of each period asset value was determined, using the urn with white and yellow balls. Subjects then computed their cash balances and carried them forward to the next period.

A complete set of instructions, profit computation sheets, and forms to play each type of auction were provided to the participants. These instructions and actual operationalization of the markets closely followed the practice in experimental economics (see Plott 1982, 1986).

## 3. Results

For each of our 14 experiments, we analyzed individual bids, market prices, and the distributions of the number of units of assets that traders held at the end of trading periods. For the sake of brevity we will provide a summary of results for all experiments and report details only for some experiments.

### A. Aggregate Results

In Table 3, the mean prices for unambiguous and ambiguous assets are reported for the first and last period and averaged over all periods. For $p = 0.5$ (excludes experiments 2, 4, 6 and 8 for which $p = 0.05$), the mean price averaged over all periods was lower for the ambiguous assets in each of the 10 experiments. Further, except for experiment 13, in each of the remaining nine experiments, the mean price for the ambiguous asset was lower in *every* period. The price for the ambiguous asset, however, seemed to increase from the first trading period to the last trading period. For example, in experiment 1, the price in the first period was DM 10 and it increased to DM 50 in the eighth period. In most but not all experiments, the price differential between unambiguous and ambiguous assets seemed to shrink from the first to the last period. In one experiment (13, double-oral, independent) this price differential vanished completely.

## B. Low Probability Gambles

Experiments 2, 4, 6 and 8 involved assets that yielded DM 100 with a 0.05 probability (or mean probability) and DM 0 with a 0.95 probability. The mean price averaged over all periods was higher for the ambiguous asset in three experiments and lower in one (experiment 8). The prices, however, converged rapidly. For example, in experiment 4, the prices for two types of assets were exactly DM 5 in each of the last four periods. It is to be noted that individual level studies (Einhorn and Hogarth 1985, Curley and Yates 1985, Kahn and Sarin 1988) found that prices (or certainty equivalents) for ambiguous assets tend to be higher at low probabilities. In our experiments, we find no systematic differences in the market price for the two types of assets. Thus, in market settings the effect of ambiguity seems to wash out at low probability levels. This finding is not inconsistent with Einhorn and Hogarth's (1985) model, as it is quite possible that the decision weight function crosses over the diagonal (from ambiguity seeking to ambiguity averse region) at our chosen $p$-level (see also Hogarth 1989).

## C. Experienced Subjects

The participants in experiments 9 and 10 were experienced bond traders. In experiment 10, the ambiguity in probability was defined by specifying three estimates of probability given by three different experts. In both experiments 9 and 10, the ambiguous asset had a lower price. We found it surprising, however, that in experiment 10 the market price for the ambiguous asset was approximately half of the market price for the unambiguous asset in spite of the fact that the two had the same mean probability 0.5 of yielding a payoff of DM 100. Because of constraints on executives' time, these experiments were run only for three periods. We do not therefore know how experienced subjects behave in longer trading periods. Their behavior, however, in a limited number of trading periods seems to be no different than that of our student subjects. The detailed results for experiments 2, 4, 6 and 8 that dealt with low probabilities and showed no ambiguity effects and for experiments 9 and 10 with bond traders that were run only for three periods will not be reported. We now discuss, in some detail, the results of experiments 1, 3, 5, 7, 11–14.

## D. Independent Auctions

In Figures 1–4, the market prices for unambiguous and ambiguous assets in both the sealed-bid and double-oral auctions are plotted. Even though the auctions were run sequentially, the two graphs for market prices of unambiguous and ambiguous assets over time are superimposed to highlight their differences. The market prices for ambiguous assets are lower. The market prices showed convergence in the sealed-bid auctions but not in the double-oral auctions. In experiment 13, the prices for both types of assets converged to around DM 60 by the end of the last period (period 8). An examination of the final holdings of certificates at the end of each period reveals that in experiment 13, subject number 6 short-sold unambiguous assets in every period to drive down its price (see Table 4). Except for this case (experiment 13), the price differential between unambiguous and ambiguous assets in the other three experiments narrowed over time but seemed to persist. Even in experiment 13, the mean prices in the first four periods (not shown in Figure 4) were lower for ambiguous assets. Our data provide strong evidence that in initial periods of trading, the market price for ambiguous assets is lower. This price differential, however, reduces over time in independent auctions.

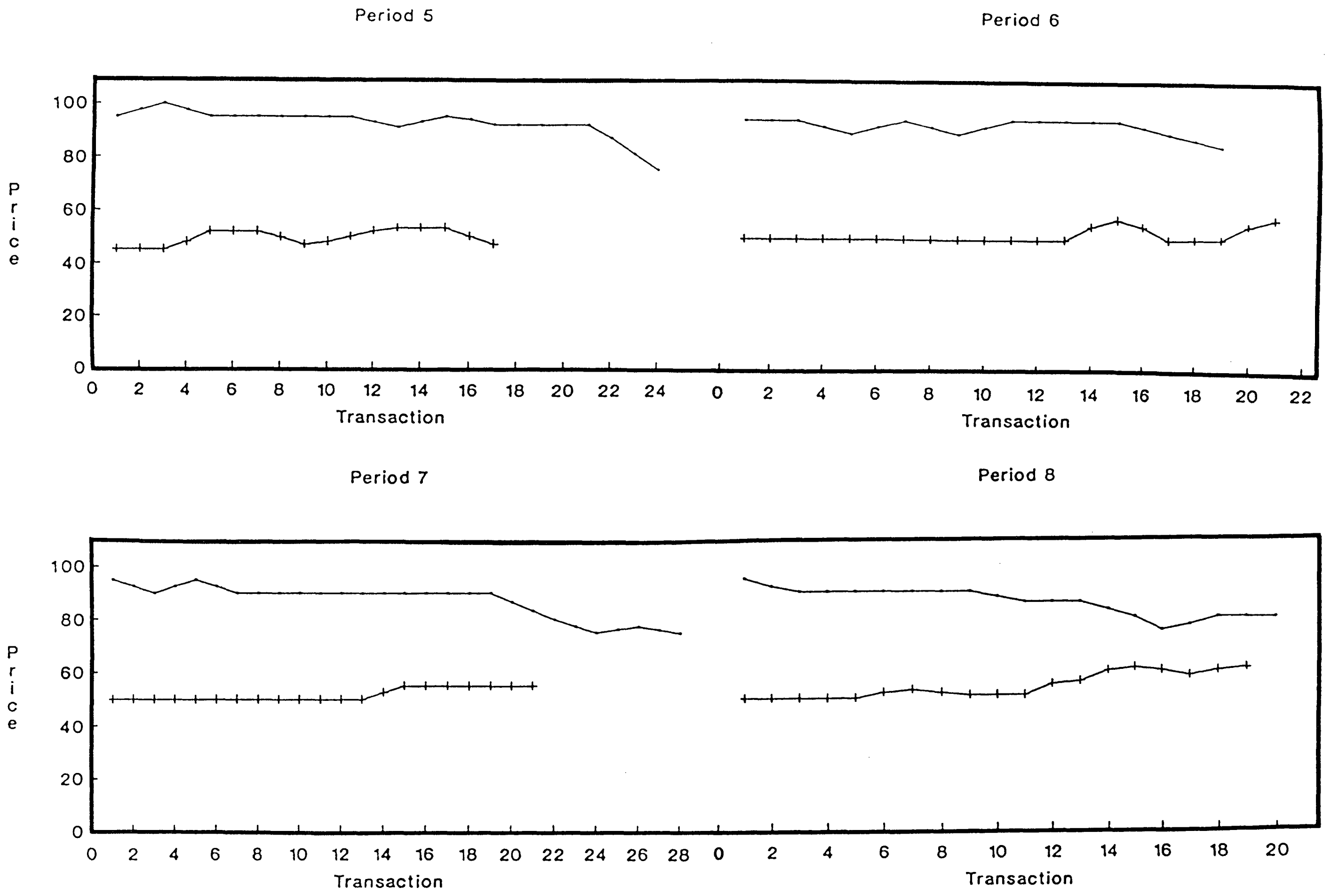
## E. Simultaneous Auctions

In simultaneous auctions both unambiguous and ambiguous assets were traded together so the comparison between the two is direct and transparent. In Figures 5–8 the market prices observed in experiments 3, 7, 12, and 14 are plotted.

In the sealed-bid simultaneous auctions, the price differential between unambiguous and ambiguous assets is striking (Figures 5 and 7). The price for ambiguous assets is approximately half the price for unambiguous assets throughout the trading periods and shows no apparent sign of convergence. Further, an analysis of individual bids shows that in experiment 7 the bid prices for the ambiguous assets were lower than the bid prices for the unambiguous assets in 63 out of a total of 64 bids (8 subjects $\times$ 8 periods). The individual bids for experiment 12 are shown in Table 5. Except for subjects 2 and 5, who bid the same amount for both assets in every period, the individual bid prices for the ambiguous asset are lower in each of the sixteen periods.

**Figure 8** Market Price for Unambiguous and Ambiguous Asset in a Double-Oral Auction (Simultaneous Case, Experiment 14)

· Unambiguous Asset
+ Ambiguous Asset




A possible explanation for the lower prices of ambiguous assets could be that in sealed-bid auctions subjects do not directly interact with each other, and that the announced market price at the end of each period does not convey sufficient information on individual bid prices. Thus, the market force is not strong enough to induce rationality in such situations. However, a comparison of market prices of the two types of assets in the double-oral auction, that allows for a more vigorous interaction among traders, still leads to the same conclusion (see Figures 6 and 8). Further, an analysis of individual bids and the number of units held by each subject reveals that no individual attempted arbitrage by accumulating the units of ambiguous assets and short-selling the units of unambiguous assets.

It seems that a more transparent comparison between the unambiguous and ambiguous assets leads to a greater differential in market prices (simultaneous versus independent) contrary to our expectation. Subjects seem to regard an ambiguous asset as an inferior (or more risky) good, and thus are willing to pay less for it.

## F. Asset Allocation

In Table 4, the distribution of the number of units of unambiguous and ambiguous assets among participants for each of the 14 experiments is reported. The pattern of individual holdings when analyzed period by period reveals that only a minority of our subjects recognized the equivalence of unambiguous and ambiguous assets.

**Table 5** **Individual Bids in Experiment 12 (Underlined Subjects Received One Certificate)**

| Student | | Period 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | red | 7.50 | 52.00 | 51.00 | 52.00 | 52.00 | 52.00 | 50.00 | 50.50 | 50.50 | 50.50 | 50.50 | 51.00 | 50.50 | 50.00 | 50.50 | 50.50 |
| | green | 1.20 | 27.00 | 26.00 | 27.00 | 27.00 | 29.00 | 26.00 | 29.50 | 30.50 | 30.50 | 31.50 | 31.00 | 31.50 | 27.00 | 27.50 | 28.00 |
| 2 | red | 49.99 | 49.99 | 49.99 | 49.99 | 49.99 | 49.99 | 49.99 | 49.99 | 49.99 | 49.99 | 49.99 | 49.99 | 49.99 | 50.00 | 49.99 | 49.99 |
| | green | 49.99 | 49.99 | 49.99 | 49.99 | 49.99 | 49.99 | 49.99 | 49.99 | 49.99 | 49.99 | 49.99 | 49.99 | 49.99 | 50.00 | 49.99 | 49.99 |
| 3 | red | 50.00 | 51.00 | 51.00 | 30.00 | 52.00 | 30.00 | 45.00 | 51.00 | 51.00 | 40.00 | 51.00 | 51.00 | 40.00 | 50.00 | 51.00 | 40.00 |
| | green | 30.00 | 30.00 | 20.00 | 20.00 | 0 | 20.00 | 10.00 | 10.00 | 15.00 | 20.00 | 10.00 | 10.00 | 20.00 | 26.00 | 20.00 | 22.00 |
| 4 | red | 55.00 | 50.00 | 56.00 | 52.00 | 57.00 | 49.00 | 51.00 | 30.00 | 52.00 | 40.00 | 52.00 | 40.00 | 50.70 | 40.00 | 50.50 | 50.99 |
| | green | 25.00 | 35.00 | 30.00 | 25.00 | 35.00 | 26.00 | 29.00 | 10.00 | 30.00 | 33.00 | 29.98 | 30.50 | 30.50 | 27.00 | 29.50 | 28.00 |
| 5 | red | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 |
| | green | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 |
| 6 | red | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.00 | 50.01 | 50.01 | 50.51 |
| | green | 10.00 | 15.00 | 25.00 | 25.00 | 26.00 | 32.00 | 28.00 | 34.00 | 10.00 | 22.00 | 25.00 | 32.00 | 25.00 | 25.00 | 25.50 | 25.50 |
| 7 | red | 45.00 | 45.00 | 55.00 | 55.00 | 53.00 | 50.00 | 51.00 | 51.00 | 50.00 | 50.00 | 51.00 | 51.00 | 45.00 | 50.00 | 51.00 | 51.00 |
| | green | 35.00 | 30.00 | 35.00 | 30.00 | 30.00 | 30.00 | 29.00 | 25.00 | 25.00 | 33.00 | 30.00 | 31.00 | 25.00 | 28.00 | 29.00 | 28.00 |
| 8 | red | 70.00 | 70.00 | 70.00 | 70.00 | 30.00 | 30.00 | 70.00 | 60.00 | 25.00 | 25.00 | 60.00 | 60.00 | 49.00 | 49.00 | 60.00 | 60.00 |
| | green | 10.00 | 35.00 | 25.00 | 27.00 | 30.00 | 31.00 | 31.00 | 31.00 | 31.00 | 31.00 | 32.00 | 32.00 | 25.00 | 24.00 | 25.00 | 23.00 |
| Price | red | 50.00 | 50.00 | 51.00 | 50.00 | 50.00 | 49.99 | 50.00 | 50.00 | 59.00 | 49.99 | 50.50 | 50.00 | 49.99 | 50.00 | 50.50 | 50.50 |
| | green | 25.00 | 30.00 | 26.00 | 27.00 | 30.00 | 30.00 | 29.00 | 29.50 | 30.00 | 31.00 | 30.00 | 31.00 | 25.00 | 27.00 | 27.50 | 28.00 |
| Value | red | 100 | | 100 | | 0 | | 100 | | 0 | | 100 | | 100 | | 0 | |
| | green | 0 | | 0 | | 0 | | 100 | | 0 | | 0 | | 100 | | 0 | |

An example is individual 6 in experiment 13 who took advantage of the higher price of unambiguous assets by short-selling them. The distribution of asset allocation seems fairly typical in all of our experiments.

We also analyzed the impact of asset value revealed in a period on the bids and market prices for the subsequent periods. We observed no evidence of interaction between the results of the resolution of asset value (DM 100 or DM 0) and the individual bids and market prices in the subsequent periods. This may be because after each resolution the composition of urns is changed for the next period. Thus, in our experiments ambiguity does not diminish over the trading periods.

## 4. Conclusion

In many real-world situations managers and individuals make decisions in market settings (e.g., bidding for oil leases and mineral rights, auctions for real estate and art objects, and contract procurements). In this paper we examined the bidding behavior of individuals and the resulting market price when the object of sale has some degree of ambiguity in probability of payoffs. Specifically, we employed the experimental strategy with business students and bank executives as subjects to test whether the individual bid prices and the market price for an unambiguous and an ambiguous asset with identical *mean* probabilities would be the same, as predicted by the theory of decisions under uncertainty (Savage 1954). Our finding is that the individual bid prices as well as the market price for an ambiguous asset were consistently below the corresponding individual bids and market price for an unambiguous asset when the probability of gain was 0.5. This result held regardless of the type of market mechanism employed (sealed-bid or double-oral) and whether the two types of assets were auctioned independently or simultaneously. For the independent case, though, we observed some convergence in the market price over time.

What possibly could be the reason for this deviation from the rational theory of decision making? We believe that people regard an ambiguous asset as more risky. The ambiguous asset has a potential to induce psychological discomfort (since the nature of the stochastic process is unknown) as well as regret due to hindsight. Several other researchers have provided explanations for ambiguity aversion (see for example, Fellner 1961, Smith 1969).

Our results suggest that the market forces alone may not be sufficient to wash out the effects of ambiguity on decisions. In descriptive theory, one may recognize that psychological well-being interacts with economic well-being in a fundamental way and therefore the theory needs to be suitably modified to account for psychological effects. Some attempts to modify SEU theory to accommodate effects of ambiguity have been made recently (see Schmeidler 1989, Einhorn and Hogarth 1985, Luce and Narens 1985, Fishburn 1988). Our results suggest that predictions of economic models may be improved by incorporating more flexible assumptions about individuals' behavior. Our work is of managerial interest as it provides insights into what a manager can expect in bidding or other market situations where the object of sale involves ambiguity in probability due to, for example, lack of information or experience.[1]

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