Ambiguity about Informed Trading in Dealer Markets - 
An Experiment

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Abstract

We use an economic experiment to examine the impact of an ambiguous level of asymmetric information on the behavior of security dealers. Specifically, we distinguish three types of uncertainty with respect to informed trading: risk, compound risk, and ambiguity; for both a monopoly and a duopoly market setting. We find that dealer’s bidding behavior is less aggressive under an ambiguous level of informed trading than a risky level of informed trading. Additionally, we find that the stochastic nature of choice can hinder our ability to observe a difference in dealer behavior between the risky versus ambiguous level of asymmetric information in dealer markets.

JEL Classification Codes: G24, D82, D40

Keywords: Uncertainty; Ambiguity; Risk; Market Experiments; Dealer Markets.

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1 Introduction

In most major financial markets, such as the NYSE and the NASDAQ, dealers play a central role in making markets. Whether and to what extent dealers choose to make markets by posting quotes for securities determine the liquidity and performance of the market, including whether the market will shut down under duress. One of the most dramatic and famous examples of a market breakdown is the “flash crash” of May 6th 2010, when liquidity vanished in an instant, leading to a plunge of the Dow Jones Industrial Average by 1000 points (~9%), only for those losses to be recovered twenty minutes later. A detailed study by Easley et al. (2011) suggest that the key reason for the crash was the exit of liquidity providers due to uncertainty about order toxicity (probability of informed trading) and that the crash would have been avoided had liquidity providers remained in the marketplace. In contrast to the use of indirect measures of informed trading based on actual transaction data such as probability of information-based trading (PIN) in Easley et al. (1996) and subsequent empirical proxies\(^1\), our study seeks to analyze the probability of informed trading in dealer markets directly by explicitly manipulating this central factor through the use of experimental markets.

In this paper, using a controlled laboratory experiment, we examine the behavior of security dealers who are uncertain about the level of asymmetric information in the market and have an option to exit the market at their discretion. The framework from which our experiment is built hinges on the idea that the traditional treatment of risk, where knowledge of underlying probabilities is required, is ill suited to reflect the chaotic environment that surrounds an event like the “flash crash” of 2010. Furthermore, we distinguish the uncertainty about the asset value, which remains the same with respect to the underlying asset volatility, from a sudden change in uncertainty with respect to the degree of asymmetric information, which can cause the dealers to withdraw their provision of liquidity (quotes) in the market, causing a market breakdown.

Asymmetric information is by its nature hard if not impossible to detect in field data. In this scenario, controlled laboratory experiments provide a useful way to generate consistent data where severe asymmetric information can be clearly specified and controlled. Our research is designed to shed light on the effect of uncertainty with respect to the level of asymmetric information on the market liquidity and transaction costs faced by traders. We model uncertainty with respect to informed trading as risk, compound risk, or ambiguity using urns whose composition is either known or unknown to the participants. Specifically, we construct the risky (\(R\)) urns, whose exact composition is known to the participants; the compound (\(C\)) urn, whose composition “process” is known; and the ambiguous (\(A\)) urn,

\(^1\) Easley et al. (2012) developed the volume synchronized probability of informed trading (VPIN) to use as a short term indicator of order toxicity in high frequency markets, which they suggested was the primary reason for the ‘flash crash’ of 2010. Alternative recently developed measures such as intra-day probability of informed trading (PROBINF) by Kumar and Popescu (2014) also seek to empirically determine the level of information asymmetry.
whose composition process is unknown. Thus in a risky and a compound situations, the probability distribution is objectively known, while in an ambiguous situation it is not.

In this paper we ask the question “what is the role of uncertainty about informed trading in dealer market liquidity”? To answer this question we build a simple version of a financial market where dealers face uncertainty with respect to the level of informed trading. The value of the asset that they trade is drawn from a distribution with known mean and variance. Given the well-known fact in market microstructure literature that liquidity has multiple dimensions (e.g. “Market liquidity is a slippery and elusive concept, in part because it encompasses a number of transactional properties of markets” (Kyle (1985)), we focus on two of its dimensions: (i) resiliency, measured as the fraction of time a market is open and (ii) price. Our main goal is to answer the question: Are there any differences in market liquidity within environments where the level of informed trading is viewed as risky, compound, or ambiguous? That is, we compare the three uncertainty scenarios about the informed trading across the two dimensions of market liquidity.

Prior theoretic research (Glosten (1989)) for environments with risky informed trading leads us to predict that a concentrated dealer market such as a monopoly specialist will have higher trading cost but be more resilient in environments where asymmetric information is high, while a dispersed dealer market with multiple dealers will break down more often but offer lower trading costs. Whether this fundamental trade-off in resiliency and trading cost actually exists under ambiguity, though, is an empirical question we intend to explore. Related experimental studies to ours have been conducted by Cason (2000), Krahnen and Weber (2001), Schnitzlein (2002), and Sheh and Wilcox (2009), who consider dealer markets in an asymmetric information environment. Cason (2000) finds that markets organized by dealer intermediaries are sufficiently competitive to generate high informational efficiency, even when informed traders could not post limit orders. Schnitzlein (2002) examine market liquidity in a continuous dealer market experiment where there is uncertainty about the presence and number of informed traders. Their main focus is on the strategic considerations from the informed trader (insider) perspective which revolves around dealers falsely inferring presence or absence of insiders. They find that market outcomes are similar to the case when the number of insiders is known. Krahnen and Weber

\footnote{The C urn was composed as follows: two urns of known compositions (one with 1 black marble and 2 white marbles and one with 2 black and 1 white marbles) are placed in a box and one is randomly drawn by a participant to be the C urn used for the draws. The A urn was composed as follows: one marble is placed in the urn prior to start of the experiment and the only information provided to the participant is that it could be either black or white. During the experiment subjects verify that there is one marble in the urn by touching it, and observe one black and one white marbles added to the urn. Thus, the outcome space is the same between the C and the A urns, however, unlike the C urn, no objective probabilities are given for the composition of the A urn - there is ambiguity about the number of black marbles.}

\footnote{For our experimental design, trading cost is inversely related to the bid amount. That is, the higher the bid quote, the lower the trading cost.}

\footnote{The dimension of liquidity examined in Schnitzlein (2002) is measured in terms of price change per unit order flow on price continuations.
find that competition among market makers (4 dealers vs. 1 dealer) in an asymmetric information environment significantly reduces the bid-ask spread, and increases the transaction volume. However, because dealers do not have an option to exit the market, competitive undercutting leads to a net trading loss for market markers on average. When allowing dealers to exit the market at their discretion, Sheh and Wilcox (2009) find that a duopoly market structure is more resilient than a monopoly market structure in an asymmetric information setting in terms of liquidity provision. But dealers in these experiments were told exactly the level of informed trading in the market and did not have to worry about this source of uncertainty. This is clearly not reflective of what occurs in actual financial markets, where dealers have to constantly assess and react to potential informed traders based on limited information. We believe that this is a crucial factor that needs to be examined closely to facilitate a deeper understanding with respect to the uncertain environments where market breakdowns occur.

Decision making under ambiguity has recently gained considerable attention from both the individual (Halevy (2007), Eichberger et al. (2013), Eliaz and Ortoleva (2012)) and the market (Bossaerts et al. (2010), Corgnet et al. (2012), Kocher and Trautmann (2013), Füllbrunn et al. (2014)) perspectives. In contrast to the aforementioned literature on ambiguity in asset markets, where the source of ambiguity is the value of the asset, our key contribution to this literature is to change the focus of ambiguity to the level of informed trading (which is similar in nature to Schnitzlein (2002)). We do so by comparing dealer markets where informed trading is presented as pure risk, compound risk, and ambiguity. In particular, Bossaerts et al. (2010) study the impact of heterogeneity of ambiguity attitudes and ambiguity aversion on equilibrium asset prices in competitive financial markets, implemented as a continuous double auction. They find that by refusing to hold an ambiguous portfolio ambiguity averse investors have a significant effect on prices. Corgnet et al. (2012) investigate trader reaction to ambiguity when dividend information is revealed sequentially. They find no significant differences between risky vs. ambiguous assets regarding prices, price volatility, and trading volume. Kocher and Trautmann (2013) experimentally study subject’s self-selection into first-price sealed-bid auction5 for both a risky and ambiguous prospect, and find that most select to submit bids to the risky as opposed to the ambiguous prospect, which lead to thinner markets for the ambiguous one. Füllbrunn et al. (2014) find two key conditions for ambiguity effects to survive in asset markets: that ambiguity attitudes should be sufficiently biased towards

5 Kocher and Trautmann (2013) states: “The one-shot auction design is applied because of the inherent uniqueness of ambiguous situations and because it avoids possible biases in learning with repeated auctions.” This is the reason why we use a first-price sealed bid auction in our experimental design and eliminate payoff feedback.
ambiguity aversion and that the feedback of other market participants needs to be limited. In summary, while all of the above studies consider an asset’s value as ambiguous; we, on the other hand, consider the impact of ambiguity with respect to the level of informed trading while the asset’s value in question is known to be risky, not ambiguous. Additionally, none of these studies focus on the stochastic nature of the trader’s decisions in the market, and their implications on the market outcome, which we do in this study.

The importance of the stochastic nature of subjects’ decision cannot be overstated, as it turns out to be the key factor that allows us to disentangle an otherwise perplexing set of results. This is in line with a growing amount of literature that has documented the importance of the stochastic part of decision under risk; as Wilcox (2011) states succinctly: “I regard stochastic choice as the oldest and most robust fact of choice under risk, and believe that serious interpretive errors can occur when the implications of stochastic choice models are ignored.” We investigate what effect does the precision of decision-making, and resulting strategic uncertainty, has on market liquidity. We show that subjects refine their decision making process from early rounds to the late rounds, even without payoff feedback, which reduces strategic uncertainty and results in a significantly different equilibrium distribution of prices. By accounting for the precision we are also able to find a difference in dealer behavior between risky and ambiguous informed trading environments. Finally, we use behavioral estimates of precision obtained from binary choice decisions as an input to the Quantal Response Equilibrium model of McKelvey and Palfrey (1995) to build a meaningful benchmark to help us explain human subject behavior in the experimental dealer markets.

The rest of the paper is organized as follows. In Section 2 we introduce the environment and potential challenges when incorporating risk aversion and stochastic choice on the part of the dealer. In Section 3 we describe the experimental design and present an overview of the data. In Section 4 we present and discuss theoretical predictions and results. Finally, in Section 5 we conclude.

## 2 Environment

In this section we present the environment and demonstrate potential challenges when testing for differences in behavior which could arise from stochastic nature of choice and subjective beliefs about an uncertain process.

### 2.1 Asset

The underlying risky asset has a payoff $V \in \{H, L\}$ at the end of the period. Specifically, the asset pays $H$ with probability $q$ and $L$ with probability $(1 - q)$.

### 2.2 Agents
The agents that interact in a market setting are *Dealers* and *Traders*. Particularly, dealers are part of the market structure itself, while traders can be thought of as general population interested in selling/purchasing the asset.

A Dealer, or Market Maker, is a market specialist who provides a Bid and Ask quote on the asset prior to the revelation of the true value. While in reality, Dealers place a Bid and an Ask quote, in this paper we will be focusing on the bid side in our experiment. Dealer can earn a profit through market operations (Quotes), but also has an outside option that pays $S$ at the end of the period.

Traders buy or sell one unit of asset for their personal motives. As is common in market microstructure literature (O’Hara, 1995), we will distinguish between *informed traders* (insiders) who know the true $V$ and *uninformed traders* (outsiders) who do not know the true $V$ but have private (liquidity) reasons to trade the asset. The *informed trader* knows something that neither the uninformed trader, nor the dealer knows - the true $V$ for the trading period. He optimally exploits this privileged “insider” knowledge to maximize his own trading profits, by selling the asset at the bid quote if $V$ is lower than the bid price. The *uninformed trader*, on the other hand, will sell the asset to the market maker at the best bid quote. Thus a Dealer is facing an adverse selection problem, and his decision depends on his belief about the likelihood the trader is informed, which we will denote by $p$.

![Figure 1: Timeline.](image)

The timeline of the four key stages within each period is presented in Figure 1. First, dealers decide to either provide a bid quote or to opt-out. Next, asset value, $V$, is revealed to the *informed trader*. Then traders decide whether to enter the contract (sell the asset) at the posted price. And finally, $V$ is revealed to everyone and profits and losses are realized for the period. Thus, if the asset was acquired, the Dealer earns $(V - b)$, where $b$ is the bid amount.

### 2.3 Markets

Three market structures considered in this study differ with respect to the decision complexity and strategic complexity. Specifically, we consider the binary choice ($B$) structure, the monopoly ($M$) structure and the duopoly ($D$) structure. We present the dealer decision problem for each structure in Sections 2.3.1, 2.3.2, and 2.3.3 respectively.

#### 2.3.1 Binary Choice
The Binary Choice market structure is equivalent to an ultimatum bargaining where Dealer is deciding whether or not to accept an exogenously specified selling price (choose to bid $b$) or opt-out and receive his outside option. Figure 2 presents the Dealer's decision in the Binary Choice market structure.

**Figure 2: Binary Choice.** Dealer chooses between placing a bid, $b$, and taking an outside option, $O$. Asset value is $H$ with probability $q$, and $L$ with probability $1-q$. Trader is Informed with probability $p$ and Uninformed with probability $(1-p)$. Source of $p$ will vary by uncertainty treatment, while $q$ will be known and constant for all treatments.

The expected utility of a bid, $b$, and outside option, $O$, is given by equations (2.1) and (2.2) respectively:

$$EU_B(b) = q(1-p)u(W + H - b) + qpu(W) + (1-q)u(W + L - b)$$  \hspace{1cm} (2.1)

$$EU_O = u(W + S)$$  \hspace{1cm} (2.2)

where $W$ is Dealer's endowment in the period, $\{H, L\}$ are asset value realizations, $S$ is payoff of the outside option, and $u(.)$ is the utility function. Thus, the Dealer chooses the option with the highest expected value given her current beliefs $p$ and $q$. The uncertainty about the trader type ($p$) will be the key element of our experimental design and will be described in detail in Section 3.1.

The binary choice market structure is the simplest environment presented to the subject: it lacks the strategic element as well as the complexity of multinomial choice. However, it allows us to use the existing canon of work on binary choice to estimate risk preference as well as subjective beliefs in compound and ambiguous environments. Additionally, we estimate the precision with which subjects make their decision, which is also known as the “rationality” parameter. This is useful because we then can feed these estimates into a theoretical model and obtain a meaningful benchmark.

### 2.3.1 Monopoly

The key difference between the Binary Choice (B) and the Monopoly (M) market is that in the former the bid amount is fixed, while in the latter, the bid amount is determined by the dealer. Therefore, the Monopolist’s decision is a multinomial discrete choice as opposed to a binary discrete choice.
Let \( b_i = 0 \) denote Dealer choosing the opt-out option, \( O \). Then for the monopolist dealer, the expected utility of a bid, \( b_i \), is given by

\[
EU_M(b_i) = \begin{cases} 
EU_B(b_i), & b_i > 0 \\
EU_O, & b_i = 0 
\end{cases}
\]  

(2.3)

where \( EU_B \) and \( EU_O \) are given by equations (2.1) and (2.2). Then, Dealer chooses the option with the highest expected utility given her current beliefs \( p \) and \( q \). Notice that the monopolist's optimal bid will take on two values:

\[
b^* = \begin{cases} 
\min_{b_i}, & EU_B(b_{min}) > EU_O \\
0, & \text{otherwise} 
\end{cases}
\]  

(2.4)

While the optimal decision is either to provide the minimum bid possible or opt out. Under the stochastic choice framework, however, we should expect there to be deviation from the \( b^* \), in particular we should expect to observe some \( b_i > b_{min} \).

### 2.3.2 Duopoly

The key difference between the Monopoly (M) and the Duopoly (D) structures is number of dealers present in the market. Specifically, we consider a structure with two Dealers competing for the right to buy one unit of indivisible asset, from a seller. The winning Dealer gets the asset and pays an amount equal to his bid, while the losing dealer goes away with no change in his initial wealth. In case of a tie, each of the two dealers is equally likely to make the purchase. Thus, the Duopoly setting is different from the Monopoly setting in that the expected utility of the first dealer is a function not only of his own bid, \( b_1 \), but also of the bid by the second dealer, \( b_2 \).

\[
EU_D(b_1 | b_2) = \begin{cases} 
EU_M(b_1), & b_1 > b_2 \text{ or } b_1 = 0 \\
.5EU_M(b_1) + .5u(W), & b_1 = b_2 \text{ and } b_1 > 0 \\
u(W), & 0 < b_1 < b_2 
\end{cases}
\]  

(2.5)

where \( EU_M(.) \) is the expected utility of monopolist from equation (2.3). Thus, Dealer 1 (Dealer 2) chooses \( b_1(b_2) \) to maximize his expected utility given in (2.5).

The symmetric mixed-strategy Nash Equilibrium (NE) and Quantal Response Equilibrium (QRE) of this game, presented in the Figures 3, depend on the beliefs about the probability of informed trading (\( p \)) and the risk preference (\( \gamma \)) of the dealer. Specifically we consider theoretical predictions for the risk neutral and risk averse agents and two subjective beliefs corresponding to \( p = \frac{1}{2} \) ("neutral beliefs") and \( p = \frac{1}{3} \) ("pessimistic beliefs") for comparison.\(^6\)

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\(^6\) The parameters chosen are the same as will be used in the experiment: \( V \in \{\$5.00, \$0.00\} \), \( q = .5 \), \( b \in \{0, .1, .2, \ldots, 4.9\} \). The initial wealth, \( W \), is assumed to be \$5.00 because i) participants are explicitly told that they will earn at least \$5.00 and ii) participants do not learn the payoff outcome of their decisions until the after all decisions have been made.
Figure 3: Symmetric Mixed-strategy Equilibrium. The utility function is assumed to be a normalized version of the CRRA with $\gamma = 0$ for the Risk Neutral case and $\gamma = 0.5$ for the Risk Averse case (see Appendix B). The precision parameter is $\lambda \to \infty$ for the NE case and $\lambda = 15$ for the QRE case. Note: Bid Amount of zero means that dealer is choosing to take an outside option.

Consider the top left graph of Figure 3, with a sharp distinction between the two cases of subjective beliefs, it would seem that any difference in subjective beliefs would be easily identified within the duopoly set-up. The challenge arises when one considers risk aversion and the stochastic nature of choice. First, once we assume that agents exhibit mild risk aversion, which is commonly documented in the experimental literature, the difference between the two cases is reduced (bottom left). If we incorporate the stochastic nature of choice and consider the Quantal Response Equilibrium (McKelvey and Palfrey (1995)) with the precision parameter of $\lambda = 15$ the difference reduces significantly for the risk neutral agent (top right), and especially for the risk averse agent (bottom right).\(^7\)

Interestingly, the distribution of bids for a combination of low precision ($\lambda = 15$) and the “worst case scenario” subjective belief ($p = \frac{1}{3}$) is actually to the right of bid distribution of high precision ($\lambda \to \infty$) and “neutral” subjective belief ($p = \frac{1}{2}$), that is, the low precision of decision making could negate the effect of any pessimism associated with an ambiguous environment. Later we will present evidence that suggests that low dealer precision is a crucial factor that limits our ability to detect ambiguity aversion effects. We see this emphasis on the precision of dealer decision making to be a unique and important contribution of this study to our understanding of the uncertainty of informed trading in dealer markets.

\(^7\) The choice of $\lambda = 15$ is for demonstration purposes and is motivated by the estimates from Section 4.3.
An important question from the experimental design perspective, is whether we expect to distinguish between the equilibrium behavior for the “neutral” and the “pessimistic” scenarios at all? In other words, given two samples of i.i.d. bids drawn from the “neutral” and “pessimistic” bid distributions (e.g. Figure 3), what is the minimum precision at which we can statistically detect any difference? Alternatively, what is the sample size required to distinguish between the two bid distributions for a given precision parameter? To help answer these questions we conduct a simulation experiment by drawing a sample of \( n=100 \) from distributions for the “neutral” and “pessimistic” subjective beliefs and a given precision parameter (\( \lambda \)) and find the \( p \)-value associated with the Kolmogorov-Smirnov test. We repeat this 100 times and plot the average as well as 95% confidence bands for different values of \( \lambda \). Results are presented in Figure 4.

![Figure 4: Effect of \( \lambda \) on our ability to distinguish between bid distributions generated from “neutral” and “pessimistic” beliefs. Bounds represent the 95% confidence interval around the mean. Bounds are obtained using nonparametric bootstrap. Notice that as \( \lambda \to \infty \), QRE\( \to \) NE.](image)

Thus, our ability to reject the difference between the two best response functions with 100 observations is limited when the precision with which agents make their decision is low. The challenge is even greater when we consider risk aversion: “Risk Averse” line is to the right of the “Risk Neutral” line in Figure 4. In our study we will estimate the precision with which agents make their bid decisions from the binary choice part of the experiment. We will then verify whether the sample size is sufficient for us to expect the difference to be significant.

3 Experimental Design

The purpose of this paper is to investigate dealer behavior; therefore we use human participants in the role of Dealers, while role of Traders is predetermined (for both informed and uninformed). The Trader type is determined by the color of the marble drawn from a physical urn as follows: a black marble denotes
Informed Trader and a white marble denotes Uninformed Trader. The rule for transactions is “the uninformed trader will always sell the asset while the informed trader will only sell the asset if the asset value is less than Dealer’s bid”. In this way the informed trader exploits his private knowledge for his own profit.

3.1 Uncertainty about informed trading

The uncertainty about informed trading is implemented as risk, compound risk, or ambiguity. The three scenarios are implemented as physical urns containing black and white marbles. We assume that if a black marble is drawn the trader is informed, and if a white marble is drawn the trader is uninformed. Thus, urns differ based on the information regarding their composition. Specifically, the three types of urns are: risky (R) urns, whose exact composition is known to the participants; compound (C) urns, whose composition “process” is known; and ambiguous (A) urns, whose composition process is unknown.8

![Figure 5: Urns.](image)

Presented in Figure 5 are the R urn, the C urn, and the A urn used in the experiment. The R (risky) urn contains 1 black marble and 1 white marble. The C (compound) urn is constructed as follows: among two bags, first containing 2 black marbles and 1 white marble, and second containing 1 black marble and 2 white marbles, one is picked at random by a participant. And the A (ambiguous) urn is constructed as follows: one marble (either black or white) is placed in the urn before participants come into the lab, then 1 black marble and 1 white marble are added to the urn in front of the participants. An example of the instructions is provided in Appendix A.

3.2 Treatments

Treatments of the experiment differ based on the type of decision made by the participant, the type of uncertainty, and the order of presentation. Specifically, we consider a duopoly (D) and a monopoly (M), as well as a binary choice (B) for each of the uncertainty scenarios presented in Section 3.1. Table 1 summarizes the nine possible combinations.

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8 The C urn was composed as follows: two urns of known compositions (one with 1 black marble and 2 white marbles and one with 2 black and 1 white marbles) are placed in a box and one is randomly drawn by a participant to be the C urn used for the draws. Unlike the C urn, no objective probabilities are given for the composition of the A urn - there is ambiguity about the number of black marbles.
A participant is faced with five decision tasks for each of the treatments of Table 1. In each decision task, the dealer needs to decide on whether to place a bid \(b_i\) or to Opt out \(O\). For the Monopoly and the Duopoly treatments the bid amounts are allowed to be between $0.10 to $4.90 in increments of $0.10. Duopoly pairs are randomly re-matched each round. The feedback provided after each decision is limited to the bid amount(s), this way we focus on subject’s reaction to uncertainty and minimize learning and income effects.

Table 2 presents a summary of the decision task parameters used in our experimental design, note that the while the asset value is risky, its probability distribution is known in all treatments, while it is the probability of informed trading in the ambiguous case that is unknown.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>Treatment</th>
<th>Value</th>
<th>Comment</th>
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</thead>
<tbody>
<tr>
<td>Probability of Informed Trading</td>
<td>p</td>
<td>C</td>
<td>(\frac{1}{3}) or (\frac{2}{3}) with known probability .5</td>
<td>Implemented as a draw from an urn</td>
</tr>
<tr>
<td>Probability of Informed Trading</td>
<td>p</td>
<td>A</td>
<td>(\frac{1}{3}) or (\frac{2}{3}) with unknown probability</td>
<td></td>
</tr>
<tr>
<td>Asset Value</td>
<td>V</td>
<td>All</td>
<td>(H = $5.00) or (L = $0.00)</td>
<td>Implemented as a flip of a coin</td>
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<tr>
<td>Probability Asset Value is H</td>
<td>q</td>
<td>All</td>
<td>(\frac{1}{2})</td>
<td></td>
</tr>
<tr>
<td>Bid Amount</td>
<td>b</td>
<td>D</td>
<td>(b \in {1, 2, ..., 4, 8, 4.9})</td>
<td>Picked by the subject</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>(b \in {0.25, 0.5, 0.75, 1.00, 1.25})</td>
<td>Exogenously specified</td>
</tr>
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</table>

Table 2: Summary of Decision Task Parameters.

With many possible order combinations we have to narrow down to a reasonable number of order treatments for our design. First, we group decisions pertaining to a specific market treatment together, this minimizes any confusion that subjects might experience for the three market structures they are in. Second, we go back to our main goal - to test differences between uncertainty treatments – and to ensure comparison validity fix order in which markets are presented. Finally, the markets of most interest in
terms of complexity of the decision are the duopoly markets therefore we keep them first. Table 3 gives a final breakdown of treatments that were used in each one of the ten sessions of the experiment.

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<td>DR</td>
<td>DC</td>
<td>DA</td>
<td>BR</td>
<td>BC</td>
<td>BA</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>12</td>
<td>30</td>
<td>$14.3</td>
<td>$7.4</td>
<td>$28.0</td>
</tr>
<tr>
<td>7</td>
<td>DR</td>
<td>DC</td>
<td>DA</td>
<td>MR</td>
<td>MC</td>
<td>MA</td>
<td>BR</td>
<td>BC</td>
<td>BA</td>
<td>10</td>
<td>45</td>
<td>$23.4</td>
<td>$10.3</td>
<td>$38.2</td>
</tr>
<tr>
<td>8</td>
<td>DR</td>
<td>DC</td>
<td>DA</td>
<td>MR</td>
<td>MC</td>
<td>MA</td>
<td>BR</td>
<td>BC</td>
<td>BA</td>
<td>8</td>
<td>45</td>
<td>$30.0</td>
<td>$22.5</td>
<td>$43.6</td>
</tr>
<tr>
<td>9</td>
<td>DR</td>
<td>DA</td>
<td>DC</td>
<td>MR</td>
<td>MA</td>
<td>MC</td>
<td>BR</td>
<td>BA</td>
<td>BC</td>
<td>10</td>
<td>45</td>
<td>$24.4</td>
<td>$5.0</td>
<td>$36.7</td>
</tr>
<tr>
<td>10</td>
<td>DA</td>
<td>DR</td>
<td>DC</td>
<td>MA</td>
<td>MR</td>
<td>MC</td>
<td>BA</td>
<td>BR</td>
<td>BC</td>
<td>10</td>
<td>45</td>
<td>$35.5</td>
<td>$18.3</td>
<td>$42.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>98</td>
<td>-</td>
<td>$25.1</td>
<td>$5.0</td>
<td>$50.6</td>
</tr>
</tbody>
</table>

Table 3: Sessions Summary. R1-9 - rounds, each corresponds to a sequence of 5 decisions; Sub - number of participants; Dec. – number of decisions made; Av./Min/Max P. – average/minimum/maximum payoff.

3.3 Administration and Data

Ninety eight undergraduate students were recruited for the experiment using ORSEE software (Greiner (2004)) on the campus of Purdue University. Ten sessions of the experiment were administered between November of 2013 and June of 2014 with numbers of participants varying between eight and twelve. The experiment was programmed and conducted by the authors using the software z-Tree (Fischbacher (2007)). All randomization were executed by physical devices (coins and urns). The payment data is summarized by session and is presented in Table 3.

Each participant made either 6 or 9 sets of five decisions. Each set of five decisions, denoted by round, corresponds to one of the cells in Table 1. Thus in total each participant made either 30 or 45 decisions. The randomization and payoffs were determined at the end of the experiment. Specifically, at the end of the experiment a coin was flipped 30 (45) times, one for each of the periods, and draws were made from an appropriate bag. The duration of the experiment was about 60 minutes with payoffs that ranged from $5.0 to $50.6 and an average payoff of $25.1.

4 Results

Table 4 present aggregate results on individual dealer bidding behavior for monopoly (M) and duopoly (D) market structures for each of the three uncertainty scenarios: risk (R), compound risk (C), and ambiguity (A).
Table 4: Individual Dealer Bids. 

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Dealer Bid %</th>
<th>Aver. Bid Amount</th>
<th>Min</th>
<th>25%</th>
<th>Median</th>
<th>75%</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR</td>
<td>0.71</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>2.1</td>
</tr>
<tr>
<td>MC</td>
<td>0.54</td>
<td>0.14</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>1.5</td>
</tr>
<tr>
<td>MA</td>
<td>0.54</td>
<td>0.14</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>DR</td>
<td>0.58</td>
<td>0.77</td>
<td>0.1</td>
<td>0.3</td>
<td>0.7</td>
<td>1</td>
<td>4.9</td>
</tr>
<tr>
<td>DC</td>
<td>0.51</td>
<td>0.6</td>
<td>0.1</td>
<td>0.2</td>
<td>0.5</td>
<td>0.8</td>
<td>4.9</td>
</tr>
<tr>
<td>DA</td>
<td>0.52</td>
<td>0.73</td>
<td>0.1</td>
<td>0.2</td>
<td>0.6</td>
<td>1</td>
<td>4.9</td>
</tr>
</tbody>
</table>

We observe that the distributions seem to differ both by uncertainty type and by market structure. In particular, when the uncertainty about the level of informed trading is presented as pure risk we obtain that human dealers choose to bid more frequently and with higher bid amounts than when the level of informed trading is presented as compound risk or ambiguity. Additionally, there is a stark difference between dealer behavior within the Monopoly and the Duopoly environments. In what follows we formally test main hypotheses of this paper.

First, in Section 4.1 we test whether market liquidity varies by uncertainty type and market structure. Second, in Sections 4.2 we test whether market liquidity varies by order of presentation. Lastly, in Section 4.3 we analyze subject behavior within the binary choice structure; specifically we obtain behavioral factor estimates for risk and uncertainty preferences. We then use these behavioral estimates to calculate the multinomial logit model and Quantal Response Equilibrium model of McKelvey and Palfrey (1995), which allows us to construct a meaningful theoretical benchmark and shed light on the nature of the learning and the effect of precision in decision making on the market outcome.9

4.1 Uncertainty Type
The main question of interest in this paper is whether there are any differences in market liquidity within environments where informed trading is viewed as risky, compound, or ambiguous? To answer this question, we focus on dealer participation (providing a bid) and bid amount distribution while holding order of presentation and market structure fixed. Figure 6 presents the data.

---

9 We do not estimate the QRE, but rather use parameters obtained from the binary choice part of the experiment to construct a meaningful benchmark to help in our understanding of dealer behavior.
Figure 6: Empirical CDF of Dealer Bids. **First/Second/Third** – order in which a set of 5 decisions corresponding to the same uncertainty setting is presented for a given market. For example, the ambiguous (A) setting is presented first in Sessions 1-4 and 10, second in Session 9, and third in Sessions 5-8. Note: Bid Amount of zero means that dealer is choosing to take an outside option.

As can be seen in Figure 6, subjects choose to provide bids more frequently in the R uncertainty treatment for all six cases. In other words, Dealer participation depends on the uncertainty type:

**Hypothesis 1A: Dealer participation varies by uncertainty type.**

Part A of our research hypothesis deals with dealer participation and the resulting market resiliency. We run a subject fixed effects logistic regression with the uncertainty type (A, C, or R), the order of presentation (1st, 2nd, or 3rd), and the market structure (M or D) as independent dummy variables and the probability of choosing to provide a bid (Bid or Opt Out) as the dependent variable. The fixed effect approach helps us deal with the fact that each individual is making multiple decisions within our experimental design and thus the unobservable individual characteristics could influence bid behavior for all his decisions. Regression results are presented in Table 5.

The coefficient on R is positive and significant (p-value of 0.000), therefore we reject the hypothesis that proportion of the time that dealers provide a quote is the same for the risky environment as compared to the ambiguous environment. At the same time the coefficient on C is indistinguishable from zero (p-value of 0.701), meaning that there is no difference between the proportions of the time subjects choose to provide a bid in the compound treatment compared to the ambiguous treatment.
A: Dealer Participation

<table>
<thead>
<tr>
<th>A: Dealer Participation</th>
<th>B: Dealer Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependent variable: Bid (Yes/No)</td>
<td>Dependent variable: Bid Amount</td>
</tr>
<tr>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>C</td>
<td>-0.059 (0.154)</td>
</tr>
<tr>
<td>R</td>
<td>0.597 (0.125)</td>
</tr>
</tbody>
</table>

p.val = 0.701  p.val = 0.429  p.val = 0.036

H1: Uncertainty

D

M | 0.461 (0.118) | D | -0.510 (0.026) |

p.val = 0.000  p.val = 0.000

H2: Market

<table>
<thead>
<tr>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>0.461 (0.118)</td>
<td>-0.030 (0.163)</td>
</tr>
</tbody>
</table>

p.val = 0.853  p.val = 0.000  p.val = 0.131

H3: Order

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.121 (0.210)</td>
<td>2,310</td>
<td>-1,280.108</td>
<td>2,574.215</td>
</tr>
</tbody>
</table>

p.val = 0.564

Observations 1,292  R2 0.616  Adjusted R2 0.584

Table 5: Subject Fixed Effects Regressions. The coefficients are relative to “A”, “D”, and “1st.” A: Dealer Participation is a binary variable. B: Bid Amount is conditional on Dealer providing a bid.

Next we consider whether Dealer bid quotes for the three uncertainty environment are different from each other. We do this by looking only at instances when a Dealer chooses to bid, in other words we consider the question of “conditional on providing a bid, are there any differences between dealer bid behavior that is due to the uncertainty being pure risk, compound risk, or ambiguous?”

Hypothesis 1B: Dealer bid amounts vary by uncertainty type.

We run a subject fixed effects regression with the uncertainty type (A, C, or R), the order of presentation within same market structure (1st, 2nd, or 3rd), and the market structure itself (M or D) as the independent dummy variables and the Bid Amount as the dependent variable. The regression results are presented in Table 5B. What we find is that the coefficient on R is positive and significant (p-value 0.036). That is, Dealers bid more aggressively when uncertainty about informed trading is generated using a risky urn than when the uncertainty about informed trading is generated using an ambiguous urn. The coefficient on C is again indistinguishable from zero (p-value 0.429). This result is consistent with finding by Halevy (2007) who finds strong association between ambiguity aversion and failure to reduce compound lotteries.

Table 5 also sheds some light on the difference between dealer behavior in the monopoly and the duopoly market structures. Specifically, at the individual level, the probability of providing a bid in the monopoly market is significantly higher than in the duopoly market, at the same time the amount of bid that is provided is significantly lower. These results corroborate previous findings of lower trading costs in competitive markets by Krahnen and Weber (2001), Sheh and Wilcox (2009) and a theoretical trade-off emphasized by Glosten (1989). At the market level, however, the fraction of time a market is open, that is
fraction of time when at least one dealer is providing a bid, is actually higher for the duopoly market than for the monopoly market.

To summarize our main results on Dealer bidding behavior, we find evidence that the type of uncertainty with respect to informed trading matters for Dealer bid provision, which in turn yields differences in market liquidity in the monopoly and the duopoly markets. Specifically, we find that resiliency and prices are significantly higher for the risky treatment when compared to the ambiguous treatment.

4.2 Order

When we consider the aggregate results in Table 4, it appears that bids are greater for MR (DR) treatment than for MC and MA (DC and DA), however, this is not the case for all sessions. Particularly, the bid amounts early-on seem to be greater than later-on. A natural question arises: how do early decisions of whether and which quote to provide differ from later decisions of the same kind? We devote this section to understanding differences that arise due to the order of presentation within each of the monopoly and the duopoly markets. Figure 7 presents the results by the market structure and uncertainty type.

![Figure 7: Holding Market and Uncertainty Type Fixed. First/Second/Third – order in which a set of 5 decisions corresponding to the same uncertainty setting is presented for a given market. For example, the ambiguous (A) setting is presented first in Sessions 1-4 and 10, second in Session 9, and third in Sessions 5-8. Note: Bid Amount of zero means that dealer is choosing to take an outside option.](image)

10 Figures C2 and C3 in Appendix C present market outcomes of each session.
Allowing order of presentation to vary within each graph we notice that when the R environment is presented first, as in Sessions 5-9, the dealer is bidding more aggressively than when the R environment is presented second or third, as in Sessions 1-4 and 10. A similar pattern holds true when Ambiguous environment is presented first, as in Sessions 1-4 and 10, as compared to when the A environment is presented second or third, as in Sessions 5-9. What may be the reason behind this difference? We argue that this is evidence of learning; specifically, subjects are refining their decision-making process, which in turn results in fewer “errors” and lower strategic uncertainty. Next we test whether the difference between order treatments are significant. We further build on this idea in section 4.3 where we estimate preference parameters in the binary choice setting under the same sequence and find that precision early-on is lower than later-on, that is participants become more “precise” with repetition.

Hypothesis 2: Dealer behavior varies by order of presentation.

We formally test this hypothesis as part of the regression results in Table 4. While, with p-values of 0.852 and 0.131 we find no evidence that Dealer participation in the 2nd or 3rd rounds is different from the 1st round, with p-values of .000 and .000 we find strong evidence that Dealer bid amounts are different across the three rounds. These results in line with Harrison et al. (1990), who document a positive effect of experience on the profitability of the monopolist price in a posted-offer market, and McKelvey and Palfrey (1995), who estimate the logistic version of the Quantal Response Equilibrium for several experiments on two-person normal form games and show that precision is lower in early rounds than in later rounds. In other words, the common conclusion in the literature is that the amount of error decreases with experience. The difference of our experiment is that participants receive almost no feedback on the effectiveness of their strategy, as so there is learning through experience is limited. Our explanation of this order effect with no profit feedback would be through the refinement of dealer decision making process, resulting in a higher precision of decision making in later rounds. In Section 4.3 we explicitly test for increased precision in a related binary choice setting.

4.3 Stochastic Choice

During the last part of the experiment each participant made decisions in the binary choice market structure, where dealers are choosing between bidding and opting out for a given bid amount. The aggregate results in Figure 8 present the fraction of participants who chose to bid as opposed to opt-out for five different values of the Bid Amount. The graph clearly shows that as bid amount increases, fewer and fewer participants choose to bid, and instead opt-out for the safe option. Another observation is that the fraction of subjects who choose to place a bid in the Risky environment is higher than both the fraction of subjects who choose to bid in compound and ambiguous environments.

11 These results are consistent with the pilot version of this experiment (Appendix E).
Figure 8: Binary Choice Decisions. Aggregate fraction of time subjects chose to provide a bid rather than opt out for each of the three uncertainty scenarios. Bounds represent the 95% confidence interval around the mean. Bounds are obtained using nonparametric bootstrap.

Table 5: Structural Estimates from the Binary Choice Decisions. γ – risk aversion; p_C – subjective belief about the C urn; p_A – subjective belief about the A urn; λ_i ∈ {R, C, A} – precision parameter.

<table>
<thead>
<tr>
<th></th>
<th>Est.</th>
<th>St.Err.</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ</td>
<td>.858</td>
<td>(.100)</td>
</tr>
<tr>
<td>p_C</td>
<td>.429</td>
<td>(.020)</td>
</tr>
<tr>
<td>p_A</td>
<td>.415</td>
<td>(.022)</td>
</tr>
<tr>
<td>λ_R</td>
<td>15.9</td>
<td>(1.8)</td>
</tr>
<tr>
<td>λ_C</td>
<td>18.5</td>
<td>(2.0)</td>
</tr>
<tr>
<td>λ_A</td>
<td>16.3</td>
<td>(1.9)</td>
</tr>
</tbody>
</table>

Using these data we formally estimate aggregate attitudes towards risk as well as subjective beliefs about compound and ambiguous environments.\footnote{Risk aversion is estimated under the assumption that subjects correctly perceive the R urn to generate p=.5. Subjective beliefs can only be estimated once the risk aversion is “pinned down”. In essence, we estimate attitudes towards compound risk and ambiguity relative to attitudes towards risk. Thus, an estimates of subjective belief of p=.405 in the ambiguous environment, is indicative of more uncertainty aversion than is captures through the risk aversion parameter, which is consistent with a pessimism or ambiguity aversion. Note, however, then for our environment, we only care about one “side” of uncertainty – which can be captured with the worst case scenario.} We follow Wilcox (2011) and estimate the contextual utility specification, which was shown to perform as well as or better than other stochastic models. Results of the estimation are presented in Table 5.\footnote{We use the CRRA utility specification normalized by the best and the worst case outcomes on each context. See Appendix B for estimation procedure.} The behavioral estimates are 1) γ - risk aversion parameter, 2) p_C – subjective belief about probability that an uninformed trader is drawn from the C urn, 3) p_A – is the subjective belief about probability that an uninformed trader is drawn from the A urn.\footnote{p_C < .5 is consistent with failure to reduce compound lotteries documented in prior studies (Halevy 2005), and is indicative of relative pessimism; p_A < .5 is consistent with pessimism and ambiguity aversion.} In addition to the above parameters, of special interest to us, is the ability to capture the stochastic nature of decision under risk. Therefore, we estimate the precision parameter, λ, for each of the three uncertainty environments, with higher λ implying higher precision of the decision making process.

We test whether subjects are compound-risk and ambiguity averse using a likelihood ratio test relative to estimates in Table 5. Specifically, we test the restricted model (p_R = p_C = p_A = .5) against the
unrestricted model presented in Table 5. With a p-value of .000 we reject the restriction in favor of the unrestricted model. Thus, there is significant evidence that uncertainty type matters. At the same time, using a likelihood ratio test we find a p-value of .528 when testing a restriction that the subjective beliefs about the compound and ambiguous environments are the same. A similar result is obtained using Wilcoxon signed-rank test— we test whether the frequency distributions in Figure 8 are the same. 15 These finding result further corroborates our result in Section 4.1, where we found no difference in market outcomes for the compound and ambiguous environments.

Next we investigate whether there is any order effect in the binary choice setting. For ease of presentation we consider two order sequences for which we had run the most sessions: ACR (Sessions 1-4) and RCA (Sessions 5-8). Figure 9 presents the frequency of subjects choosing to provide a bid versus choosing to opt out for.

When presented first, both in the ambiguous treatment (in ACR) and in the risky treatment (in RCA) we see a jagged choice pattern, which suggests that the dealers are choosing in a rather imprecise way. But as they gain experience, the pattern is smooth and more vertical, in both the ambiguous treatment (in RCA) and the risky treatment (in ACR), when they are presented third. This observation, suggests that the precision of their bids has improved. 17

---

15 Notice that Wilcoxon signed-rank test requires only independent observations to be used; therefore we look at the distribution of averages of individual subjects.

16 Likelihood ratio test between unrestricted model (12 parameters) and the restricted model (11 parameters) with the restriction being placed on the equality of the specific parameter. For example, when testing whether risk aversion is the same between the two order treatments, we restrict γ to be the same, obtain the log-likelihood and carry out the likelihood ratio test relative to the unrestricted model. P-values are presented.

17 Risk neutral agent would choose to bid for any b<1, not for b>1, and indifferent for b=1. Resulting in a vertical line at Bid=1.
The estimated aggregate preference and precision parameters for the two order treatments are presented in Table 6. We also provide p-values for a test of equality between the two estimates from the ACR and the RCA treatments. Notice that at the 5% level that only difference in precision parameters is significant. Specifically, using a likelihood ratio test obtain a p-value of .039 and .044 and thus find significantly evidence at the 5% significance level that $\lambda_R$ and $\lambda_A$ vary by order presentation. This is an important evidence of increased precision in later decisions of the experiment.

To complete our argument that order of presentation affects the market liquidity through the precision parameter we use the behavioral estimates from Table 6 as an input into two stochastic models of choice: for the monopoly we use standard multinomial logit, and for the duopoly we use the logistic version of Quantal Response Equilibrium (QRE) of McKelvey and Palfrey (1995). Model predictions and the observed data are presented Figure 8.

![Figure 10: Stochastic Choice](image)

**Figure 10: Stochastic Choice.** *Model:* predictions using structural estimates of preference and precision parameters from the Binary Choice Decisions. *Data:* aggregate data obtained from Monopoly and Duopoly markets.

Models qualitatively capture the respective order difference between the ACR and the RCA treatments that are observed in the data. In particular for the duopoly market structure in the RCA order
treatment, the Risky CDF is clearly to the right of the Ambiguous and Compound CDFs. On the other hand, in the ACR order type, Ambiguous CDF is to the right of the Risky CDF but at low bids it is almost identical. This similarity between the QRE model results and the experimental results provides clear evidence to our conclusion that the precision of decisions is a significant factor in determining dealer market outcomes. One element of the experimental data that remains unexplained by the considered models though, is the fraction of population that is choosing to opt out, particularly we observe much higher opt-out rates in the monopoly setting. The high rate of opting out behavior is consistent with the findings in Sheh and Wilcox (2009). Thus in this section we have shown that the changes in precision have a significant impact on dealer behavior and market outcomes, while potentially overriding any differences that are due to preference parameters like ambiguity aversion.

5 Conclusion

We use market experiments with human subjects in a controlled environment to clarify the impact of uncertainty with respect to the extent of informed trading on market liquidity and trader welfare in monopoly and duopoly dealer markets. Specifically, traders were either informed or uninformed and the uncertainty with respect to informed trading was generated using three types of urns: (i) a risky urn; (ii) a compound urn; and (iii) an ambiguous urn. We focused our attention to two key criteria of market liquidity - market resiliency (fraction of the time markets were open) and price (dealer bid distributions).

The main result of the paper is that after accounting for order of presentation we find differences in dealer bidding behavior depending on whether the uncertainty about informed trading is presented as risk, compound risk, or ambiguity. Specifically, when informed trading is viewed as risky the bids are the largest; when informed trading is viewed as ambiguous or compound the bids are significantly smaller. We also find evidence of an order effect – early decisions result in higher prices as compared to later decisions even without any profit feedback. We explain this phenomenon through a refinement of the participant’s decision making process which results in a more “precise” decision from a stochastic choice point of view.

We hope the insights gained by our research in this study will contribute to the discussion of how institutions themselves may interact with learning and precision of decision making. By examining the effects of ambiguity within the context of informed trading, we also hope to have shown that there are other important sources of uncertainty beyond asset values which merit further attention and study.
References


Appendix A. Verbatim Instructions (Order ACR: Sessions 1,2)

(Numbered bags hang on top of the whiteboard at all times during the experiment. Practice bag has 1 unknown ball in it. Bags #1-5 have 1 unknown ball in them. Bags #6 are empty (2 of them). Bags #7 are empty)

E1: Hello and welcome to the experimental economics laboratory. My name is [Name E1], I am [Position E1] conducting this experiment about decisions under uncertainty. In front of you is an informed consent form. It briefly summarizes the experiment. Please read it.[...wait for student to read the form...]

Your participation in this study is voluntary and you may decide not to participate in this study. If you agree to participate in this study please direct your attention to the computer screen and read the instructions.

Experimental Instructions

Today’s experiment will last about 1 hour (up to 1.5 hours). Everyone will earn at least $5. If you follow the instructions carefully you might earn even more money. This money will be paid at the end of the experiment in private and in cash. [Show Cash]

It is important that during the experiment you remain SILENT. If you have any questions, or need assistance of any kind, RAISE YOUR HAND but DO NOT SPEAK. One of the experiment administrators will come to you and you may whisper your question to us. If you talk, laugh, or exclaim out loud, you will be asked to leave and will not be paid.

Each decision task will be a choice between two options.

We will start with 3 practice rounds and go over all elements of the screen in detail. Also we will go over the compensation procedure at the end of the three practice rounds.

In the first part of the experiment (Rounds 1-15) you will be a buyer of an imaginary asset.

Practice Round 1. Let’s take a look at the options.

Option A. You can place a bid to purchase an asset from a seller. The asset pays $5.00 (Heads) or $0.00 (Tails) with 50-50% probability. Your purchase will depend on the type of the seller drawn from a practice bag.

The seller is not a person in this room; rather, the seller will act according to a simple rule based on whether he is informed or uninformed. The difference between an informed and an uninformed seller is
that, uninformed seller will always sell the asset while informed seller will only sell the asset if asset value is $0.00.

After your bids have been placed, a random draw from a bag will determine whether the seller is informed (black ball) or uninformed (white ball). For practice rounds the draw will be made from the “practice bag”. [Show the bag]

E1: Please direct your attention to E2 who will explain composition of the practice bag

**E2: Composition of the practice bag**

There is one ball of unknown color (either black or white) in this bag. [Show the bag... let a participant verify that there is one ball there by touching it] We add one **black ball** to the bag and one **white ball**. [Black ball means the seller is informed. White ball means the seller is uninformed]

To better understand this difference let us look at what happens when you select a bid. Please use the scroll bar to select bid=$1.00. The outcome table below option A describes four possible cases. The first two columns correspond to the seller being Informed. The last two columns correspond to the seller being Uninformed.

![Use the scrollbar to select your bid.](image)

**The following table summarized possible earnings for this round for Option A.**

<table>
<thead>
<tr>
<th>Outcome Table</th>
<th>Inf &amp; AV = 5</th>
<th>Inf &amp; AV=0</th>
<th>Uninf &amp; AV = 5</th>
<th>Uninf &amp; AV=0</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B &amp; H)</td>
<td></td>
<td></td>
<td>(W &amp; H)</td>
<td></td>
</tr>
<tr>
<td>Earnings ($) for this round:</td>
<td>0.00</td>
<td>-1.00</td>
<td>4.00</td>
<td>-1.00</td>
</tr>
</tbody>
</table>

Column 1) If the asset value is $**5.00** (Heads) and **Informed** trader (black ball) is drawn. Your earnings for the round will be **$0.00**. Remember that informed seller will not sell the asset if its value is $5.00 and so the sale did not go through.

Column 2) If the asset value is $**0.00** (tails) and **Informed** trader (black ball) is drawn. Suppose that you place a bid = $1.00 then your earnings for the round will be $-1.00 (what you pay to the seller) + 0.00 (your earning from the asset) = $**-1.00**

Column 3) If the asset value is $**5.00** (Heads) and **Uninformed** trader (white ball) is drawn. Remember, the uninformed seller will always sell the asset. Suppose that you place a bid = $1.00 then your earnings for the round will be $-1.00 (what you pay to the seller) +5.00 (your earning from the asset) = **$4.00**
Column 4) If the asset value is $0.00 (tails) and Uninformed trader (white ball) is drawn. Remember, the uninformed seller will always sell the asset. Suppose that you place a bid = $1.00 then your earnings for the round will be $-1.00 (what you pay to the seller) +0.00 (your earning from the asset) = $-1.00
You may change the value of your bid in which case the outcome table automatically recalculates possible earnings.
Okay so that was option A and it will become clearer as we go through the practice rounds. Now let's look option B.

**Option B, If you choose options B You receive $0.50 for the round regardless of the asset value and seller type.**
This is summarized in outcome table presented below option B. You can see that you receive $0.50 regardless of the asset or seller type.

<table>
<thead>
<tr>
<th>Outcome Table</th>
<th>B &amp; H</th>
<th>B &amp; T</th>
<th>W &amp; H</th>
<th>W &amp; T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earnings ($) for this round:</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
</tbody>
</table>

At this time please select Bid = 1.00 and click Option A. Followed by 'Submit Choice'.
Okay. Now let's take a look at the Practice Round Summary. It displays your last choice as well as the history of your prior choices together with the outcomes in a table. The outcome will be determined at the end of the experiment (practice rounds) by flipping a coin and drawing from an appropriate bag.
Please click Continue.
Okay. In practice round two please select option B and click ‘Submit choice’.
Okay. Now you can see the summary for the round and notice how your decision and the outcome table is recorded and displayed in the history table.
Please click Continue.
In the first part of the experiment you will be paired with another participant in this room. Pairs will be randomly chosen each round. Both of you will make a choice on whether to choose Option A and place a bid or to choose Option B and receive $0.50 for certain. However, the seller can only sell one asset hence he will sell to the person with the highest bid. This means that if your bid is greater than your partner’s bid the outcome will be summarized by the table below option A. But if your bid is lower than your partner's bid, the seller will not sell the asset to you so your earnings for the round will be $0.00 regardless of the type of seller and the asset value.

Please choose between Option A and select a Bid or Option B.
After you make your choice please click 'Submit Choice'.
Okay. Now you can see how your decision and your partners decision will be displayed to you during round summary and placed in the history table that you will have access too for the entire session. Note that if you and your partner place exactly the same bid one will be picked randomly and a red asterisk will denote which one was picked.

Each round 1-15 you will be re-matched with a random participant in this room.
Let us take a look at the compensation procedure. In total you will make 15 decisions in the first part of the experiment, each corresponding to one of the bags. At the end of the experiment we will flip a coin 15 times (one for each of the rounds 1-15) and make a draw from an appropriate bag. Let's do this for the practice rounds.

[Flip a coin 3 times if heads A=5 if tails A=0. Make a draw from the practice bag 3 times. Record everything]
Okay. So the earnings for the first part of the experiment will be the sum of 15 round earnings (in this case 3 rounds of practice).

In the second part of the experiment (Rounds 16-30) you will have to make a choice between two options labeled A and B that will be displayed on your screen. Each decision will pertain to one of the bags 1-7, which will be clearly stated on your screen. The earning for the second part of the experiment will be the sum of earnings in rounds 16-30.

Thus the earning for the whole experiment will be the sum of your earnings for rounds 1-30. Notice that the earnings will be determined at the end of the experiment (after all decisions have been made). In case your total earnings are less that $5 you will receive $5.

**BAG COMPOSITION**
Each round will correspond to a draw from one of these bags. Let's go through the composition.

Bag 1-5 One Unknown / One Informed / One Uninformed Seller
Bag 6 50% chance of – 2 Informed Seller (black) & 1 Uninformed Seller (white)
50% chance of – 1 Informed Seller (black) & 2 Uninformed Seller (white)
Bag 7 One Informed Seller / One Uninformed Seller

Now the tasks for which you will be compensated for will begin. Any information about current round will be displayed on your screen. In total, you will make 30 decisions that will affect your potential earnings. At the end of the experiment, the sum of your earnings for the 30 rounds will be your actual money earnings.

Please click "CONTINUE" when you are ready to begin. YOU WILL HAVE 1 minute for each round. And the time will be on top of the screen.

At the beginning of each round let participants know which bag the decision corresponds to and the composition of each bag, for example: “decision in period 1 corresponds to bag #1. Bag # 1 was composed as follows: “One Unknown / One Informed / One Uninformed Seller”. Please make your decision for period 1.”

Summary

E1:

- Right now you can see all 30 of your decisions. At this time we will make draws to determine which seller you faced in each round. And flip a coin to determine the asset value. [Flip the coins and write asset value on a board]
- b) Also, at this time we ask that you fill out the questionnaire that is being distributed.
- c) At this time we will call out participant ID#. Raise your hand when your number is called and we will bring and envelope containing your total earnings for the session.
- d) After you have completed your questionnaire and collected your earnings, you may leave.

Thank you for your participation in this experiment.
Appendix B. Estimation

When estimating the risk attitudes and subjective beliefs in Section 4.4 we consider the aggregate behavior, which can be summarized by a representative agent whose utility function is parameterized using a normalized version of the CRRA utility representation of the form:

\[ u(x) = \frac{x^{1-\gamma} - 1}{1-\gamma} \]

where \(x\) is the outcome and \(\gamma\) is the risk aversion parameter to be estimated. Thus, \(\gamma = 0\) corresponds to a risk neutral gent, and \(\gamma > 0\) corresponds to a risk averse (loving) agent. Using the contextual utility approach of Wilcox (2011) we assume that the agents perceive choices relative to the range of outcomes found in the pair of options. That is

\[ U(b) = \frac{u(b) - u(o)}{u(b_{best}) + u(b_{worst})} \]

Where \(b\) is the chosen bid, \(b_{best}\) is the available bid that generates the best possible utility, \(b_{worst}\) is the available bid that generates the worst possible utility, and \(o\) is the payoff of the outside option. Then the representative agent chooses the option with the highest expected value given her current belief, subject to an error, which is assumed to be distributed according to a logistic distribution centered at zero. Using maximum likelihood we estimate a latent structural model of choice of the form:

\[ P_b = \frac{1}{1 + e^{-\lambda \left[ EU(b) - EU(o) \right]}} \]

We pool the choices made by all participants and estimate a single set of parameters for each model, where \(P_b\) is the probability that subject chooses to bid given that she is presented with a choice: option a) bid \(b\) or b) opt-out (O). So for a given subjective belief \(p\) and we can obtain an expected utility value for the two alternatives presented. Using the Logit specification in equation above we obtain a maximum likelihood estimates of \(\gamma\) and \(p\).
Appendix C. Data

Figure C1: Binary Choice Decisions by Session

Figure C2: Monopoly - Bid Distributions by Session
Figure C3: Duopoly - Bid Distributions by Session
Appendix D. Pilot Experiment

Table D1: Order of Presentation

<table>
<thead>
<tr>
<th>Session</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order RCA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>DR</td>
<td>DC</td>
<td>DA</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>DR</td>
<td>DC</td>
<td>DA</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>DR</td>
<td>DC</td>
<td>DA</td>
<td>MR</td>
<td>MC</td>
<td>MA</td>
</tr>
<tr>
<td>4</td>
<td>DR</td>
<td>DC</td>
<td>DA</td>
<td>MR</td>
<td>MC</td>
<td>MA</td>
</tr>
</tbody>
</table>

Table D2: Data Summary

<table>
<thead>
<tr>
<th>Session</th>
<th>Subjects</th>
<th>Decisions</th>
<th>Av. P.*</th>
<th>Min. P.*</th>
<th>Max. P.*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>15</td>
<td>$17.50</td>
<td>$9.90</td>
<td>$24.30</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>15</td>
<td>$6.30</td>
<td>$5.00**</td>
<td>$15.90</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>30</td>
<td>$24.30</td>
<td>$17.00</td>
<td>$33.20</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>30</td>
<td>$15.70</td>
<td>$5.60</td>
<td>$23.60</td>
</tr>
</tbody>
</table>

Av. P. - average payoff; Min. P. - minimum payoff; Max. P. - maximum payoff; ** If participant’s cumulative earnings are negative they are subtracted from the show-up fee. In case the outcome is still negative the participant earns $0.00.

Figure D3: Bid Distribution by Market Type

Figure D4: Individual Dealer Participation