An experimental comparison of individual decisions under risk and ambiguity with and without trade.

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Abstract Previous research has examined the question of whether ambiguity-aversion affects bidding behaviour and prices in market institutions (for example, Sarin and Weber, 1993) or used market mechanisms to measure ambiguity preferences (Di Mauro and Maffioletti, 2004). The present study examines whether interactions in market institutions can eliminate ambiguity-aversion in individual decisions – an investment decision separate from bidding behaviour in the market. Alternative procedures for measuring risk and ambiguity preferences are compared with the direction of trade in experimental double auctions. This study finds that market interactions did not eliminate the affect of ambiguity on individual decisions.

Keywords: risk, ambiguity, individual rationality, experiments, markets

JEL Classification: D81, C91, C92

1. Introduction

The relationship between ambiguity-aversion and market behaviour is important for both theoretical and practical reasons. The economic importance of ambiguity has long been recognised (Knight, 1921; Keynes, 1921; Camerer and Weber, 1992; Camerer, 1998). Ellsberg (1961) demonstrated how ambiguity aversion conflicts with subjective expected utility theory (SEU), the dominant model of rational decision-making under risk and uncertainty[1]. However, Buschena (2003) noted that many individual decision experiments that demonstrate violations of expected utility theory are missing the power of market feedback, a key element in Friedman's (1953) discussion of the rationality assumption. Arrow (1986) argued that the economic concept of rationality itself relies on the market context for both its meaning and its predictive power. However, models of rationality are generally accepted as simplifications and models of market behaviour have been developed that use alternative behavioural assumptions (*e.g.*, Epstein and Wang, 1994). Although models based on rationality are incomplete, they can serve as useful first approximations for predicting market behaviour (Smith, 1991). According to Stracca (2004), the argument as to whether markets can be modelled "as if" people do follow normative decision theories is still contentious. There are also more pragmatic reasons for being interested in the relationship between decision theory and market behaviour.

Theories of decision-making under risk and uncertainty are particularly important in agricultural and environmental economics (Buschena and Zilberman, 1994; Quiggin and Chambers, 2004). Zilberman (2000) showed that even models used to estimate technological parameters necessarily make behavioural assumptions. The role of

ambiguity aversion has been demonstrated in applications to water resource management (Roseta-Palma and Xepapadeas, 2004) and environmental regulation (Stranlund and Ben-Haim, 2007). Evaluating new agricultural and environmental markets, such as water markets or pollution permit markets, requires models of the relationship between individual decisions and market behaviour. However, such models can be particularly sensitive to the choice of behavioural assumption regarding decisions under uncertainty. For example, stochastic dynamic programming (SDP) models have been used to evaluate alternative policies for water allocation in Australia (*e.g.*, Scott and Dudley, 1996). These models are particularly sensitive to the decision model assumed for price expectations (Scott, 1998)[2]. As Muth (1961) showed in formulating the rational expectations model, assumptions about expectations are vital for making predictions when information availability or other aspects of a system change.

The rational expectations model has been referred to as “the rationality postulate in stochastic dress” (Blaug, 1992, p. 231). Rational expectations are held when an objective probability law describes the state process and each individual knows this probability law precisely (Muth, 1961). A rational expectations equilibrium results when each individual bases their actions on this probability law and therefore the market equilibrium confirms each individuals’ expectations (Newbery, 1990). If an objective probability law is not assumed, then individuals’ expectations are represented by a subjective probability measure in line with the Bayesian model of decision-making (Epstein and Wang, 1994). Epstein and Wang (1994) emphasized

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[1] See Blaug (1992) for a review of the evolution of the concept of rational choice in economic theory.
[2] A model of price expectations is needed to specify the transition probabilities of prices, defined as a state variable in SDP models (Scott, 1998).

that this means that no meaningful distinction is made between risk and ambiguity. They showed that increased price volatility could result when individuals are ambiguity-averse. Such effects have substantial implications for both financial markets and for markets for water resources or emissions permits.

Although SDP models for modelling agricultural and environmental policy alternatives have generally used standard behavioural assumptions, methods are being developed for examining the effect of ambiguity-aversion as well as risk-aversion (*e.g.*, Schwarz, 2003). This is important, as policy prescriptions based on alternative behavioural models may disagree with recommendations based on more standard assumptions (Berg, 2003). The task is then to choose the most appropriate behavioural assumption for modelling interactions between individual decisions and market behaviour.

The choice of an appropriate model is complicated by the suggestion that SEU can be assumed if markets eliminate ambiguity-aversion in individual decisions over time. If this is true, then markets behave "as if" individuals conform to SEU, despite evidence to the contrary (for a review, see Camerer and Weber, 1992). A variety of ways that this form of market rationality might be maintained given behavioural anomalies have been considered (Camerer, 1987; Frey and Eichenberger, 1989; Blaug, 1992; Camerer, 1995; Cox and Grether, 1996; Di Mauro and Maffioletti, 2001; Stracca, 2004). The most common suggestion is that markets might provide information feedback and opportunities for learning via interactions with other traders that can correct biases in individual decision-making over time (*e.g.*, Di Mauro and Maffioletti, 2001).

However, others have suggested that markets do not provide the stable environment, repeated practice and experimentation, low deliberation costs, or quality of feedback that are necessary for learning (Thaler, 2000). Bounded rationality and cognitive biases may also increase transaction costs in markets (Foss, 2003). Such factors may reduce the ability of the market to eliminate ambiguity-aversion. For example, if ambiguity-aversion increases price volatility (Epstein and Wang, 1994), then this reduces the information content of price signals.

Market behaviour is ultimately produced by the interplay between institutional structure and individual behaviour. Institutions may also guide behaviour by restricting the choices of individuals to certain outcomes, and thereby 'constrain the decision space' (Loasby, 1999). Gode and Sunder (1993, 1997) demonstrated the role of institutional structures in the efficiency of the double auction. For example, the 'bid-ask spread reduction rule' requires that new bids and asks must fall within the range of prices between existing bids and asks (Gjerstad and Dickhaut, 1998; Plott and Gray, 1990). However, Brewer *et al*. (2002) presented experimental evidence that showed that whilst some structural features of markets can facilitate price convergence when there is substantial irrationality, they are not necessary for convergence with human subjects.

To examine the potential for markets to eliminate the effect of ambiguity-aversion on individual decisions it is necessary to extend previous experimental research on the relationship between ambiguity and markets. Whereas previous experiments have examined the effect of ambiguity on market prices (*e.g.*, Camerer and Kunreuther,

1989; Sarin and Weber, 1993), the present study examines the effect of markets on ambiguity-aversion in individual decisions. Sarin and Weber (1993) explicitly aimed to see whether the effect of ambiguity persists in market environments. The experimental evidence on this matter is mixed. An early study by Camerer and Kunreuther (1989) found no significant difference between the prices of ambiguous and unambiguous assets in a series of market experiments. However, Sarin and Weber (1993) observed a difference between the prices of ambiguous and unambiguous assets[3]. Their results depended on the choice of market institution, whether assets were traded simultaneously or sequentially and the probability of return used[4].

2. Review of the literature

Previous experiments have examined the effect of ambiguity on market prices and bidding behaviour in double oral auctions (Camerer and Kunreuther, 1989; Sarin and Weber, 1993), second-price auctions (Di Mauro and Maffioletti, 2004) and fifth-price sealed-bid auctions (Sarin and Weber, 1993). According to Evans (1997), the results of some experiments may have been affected by the idiosyncrasies of the market institution examined. In particular, the results of fifth-price auctions may be affected by a statistical property of this institution (Evans, 1997). Although it generally takes a number of stationary repetitions for prices to converge (Harrison, 1992), double auctions may induce rational behaviour faster than a one-sided bidding mechanism like a second-price auction (Camerer and Kunreuther, 1989). Additionally, the ability

[3] Di Mauro and Maffioletti (2001) suggested one reason for the different results might be the loss frame used by Camerer and Kunreuther (1989) compared with the gain frame used by Sarin and Weber (1993). Weber *et al*. (2000) investigated the effect of framing endowments to see whether prospect theory accurately predicted market behaviour for risky assets. Framing affected both market prices and the volume traded.

[4] Sarin and Weber (1993) reported convergence in the prices of unambiguous and ambiguous assets with a 5 percent chance of return but not for assets with a 50 percent chance of return.

of double auctions to reach a competitive equilibrium with even a small number of traders is well known (Smith, 1982).

Computerized double auctions can provide a great deal of market feedback and opportunities for learning. The complete history of market activity can be easily recorded and communicated to traders to maximize market feedback and opportunities for learning. Offers and counter-offers in a double auction can provide a great deal of information in the form of prices, bids, asks and trade volumes that is aggregated and disseminated amongst traders (Sunder, 1995). Even rejected offers communicate information (Arrow, 1986).

Sarin and Weber (1993) reported greater price differences in experiments with ambiguous and unambiguous assets traded simultaneously than when the different assets were traded sequentially. Sarin and Weber (1993) interpreted their results by reasoning that the more transparent comparison in the simultaneous auctions leads to the greater difference in prices. Sarin and Weber's (1993) results indicate that the comparative context may counteract the ability of the market to eliminate the effect of ambiguity. Although Sarin and Weber (1993) compared simultaneous and sequential trading in ambiguous and risky assets in their sequential markets, trade in ambiguous and risky assets was simply alternated. This means that subjects would still have been provided with a comparison between the two types of assets within the same experimental session.

The Comparative Ignorance Hypothesis helps explain the importance of these results (Fox and Tversky, 1995). The notion of the Comparative Ignorance Hypothesis is that

ambiguity aversion results from the direct comparison of ambiguous and unambiguous alternatives. Although, Fox and Tversky's (1995) results showed that the effect of ambiguity disappeared, Chow and Sarin (2001) concluded from their results that the effect was reduced rather than eliminated completely, without a direct comparison. These results are explained by the idea that the information advantage of options with known probabilities is more vivid in a comparative context (Chow and Sarin, 2001; Hsee, 1996; Hsee *et al*., 1999). This means that providing subjects with a ready comparison between risky and ambiguous assets would limit the ability of markets to eliminate the effect of ambiguity on individual decisions, perhaps ensuring that a difference between risk and ambiguity would be observed. Providing subjects with an easy comparison can be avoided by conducting separate experimental sessions for conditions of risk and ambiguity.

Measuring individual preferences in individual decision-making under risk and ambiguity enables further comparisons between individual and market behaviour. Epstein and Miao (2003) argued that it is inappropriate to transfer parameters of risk attitudes inferred under conditions of pure risk to conditions of ambiguity. People may see ambiguous assets as more risky than unambiguous assets, inducing psychological discomfort and regret in hindsight (Sarin and Weber, 1993). However, the empirical relationship between risk and ambiguity preferences remains unclear. There is evidence that the pattern of preferences predicted by prospect theory for risky choices over gains and losses endures under ambiguity (Di Mauro and Maffioletti, 2004). Lauriola and Levin (2001) found a positive correlation between risk and ambiguity preferences, although this relationship was only significant for some choices and was affected by subjects with extreme preferences.

Holt and Laury (2002) suggested routinely measuring subjects' risk preferences to compare with other types of decision taken by in experiments. They argued that most theorists ignore the role of risk aversion in experiments and assume that payoffs are already measured as utilities. The relevance of some measurements may depend upon the context (MacCrimmon and Wehrung, 1990; Dohmen *et al*., 2005). For example, Pennings and Smidts (2000) and Fellner and Maciejovsky (2002) both found that lottery choices were better related to market behaviour than the alternatives they considered. Although there is no standard procedure, past experiments and theory provide a number of methods that can be used in conjunction with other experimental procedures.

The difficulty of operationalizing ambiguity in experiments is generally acknowledged. A number of different methods have been used in experiments for inducing conditions of ambiguity. These include use of a second-order probability distribution (Camerer and Kunreuther, 1989), a 'best estimate' of the probability from several experts (Sarin and Weber, 1993; DiMauro and Maffioletti, 2004) and a probability interval (DiMauro and Maffioletti, 2004). Camerer and Kunreuther (1989) argued that the type of ambiguity discussed by Ellsberg is of most theoretical and practical interest. This type of ambiguity can be induced by simply not providing any information about probability to subjects. Subjects following the prescriptions of SEU should be indifferent between this type of option and an option with a known fifty-percent probability of return.

Given the results of this literature review, experiments were designed to examine the effectiveness of a computerized double auction market to eliminate the effect of ambiguity on individual decisions. Separate experimental sessions were conducted for conditions of risk and ambiguity. Under conditions of ambiguity, subjects were provided with no information about the probability of an uncertain prospect. The individual decision was framed as a choice between a certain and an uncertain prospect, which could be compared with and without market trade, under conditions of risk and ambiguity.

3. Experimental hypotheses

Experiments were designed so that a number of hypotheses regarding the effect of markets on individual decisions and the relationship between risk and ambiguity preferences and market behaviour could be tested. The experimental market is constructed so that no additional differences in values are induced to motivate trade – transactions will occur only because of endogenous differences between individual subjects. Measured preferences, the existence of trade in the market and comparisons of the direction of trade can be used to test hypotheses about the relationship between risk and ambiguity preferences and market behaviour. In the double auction, trade occurs between one buyer and one seller rather than via a pooled price (Smith *et al*., 1982) so that each trade can be compared with measured preferences. A range of risk and ambiguity preferences over the range of payoffs used in the experiments is necessary for trade. The first two hypotheses concern subjects' preferences and their relationship with trade.

Hypothesis 1: Subjects will have heterogeneous preferences over risk and ambiguity for the level of incentives used in the experiment.

Hypothesis 2: Trade will be observed in the direction from subjects with lower certainty equivalents and measured preferences for risk and ambiguity to subjects with relatively higher certainty equivalents or measured preferences.

The third and fourth hypotheses test the effect of providing objective probabilities and the effect of market trade.

Hypothesis 3: Subjects will invest more in an uncertain investment option when the probability of investment returns is known (risk) than when the probability is unknown (ambiguity).

Hypothesis 4: Subjects will invest more in an uncertain investment option with trade than without trade.

The fifth hypothesis tests the effect of market interactions on individual decisions. If the market eliminates the effect of ambiguity, then any observed difference between risk and ambiguity would not be observed in the market treatment. The interaction between the information and market effects would be significant.

Hypothesis 5: There will be an interaction between the information treatment and the market treatment. The difference commonly observed between conditions of risk and

ambiguity in individual decisions taken in isolation will not be observed in individual decisions taken whilst interacting in markets.

4. Experiment design

A 2 x 2 factorial experiment design was chosen with separate treatment conditions for the information provided about probabilities (risk or ambiguity) and the market treatment (trade or no trade). Each experimental session consisting of a series of procedures to measure attitudes to risk and ambiguity, followed by five repeated investment decisions. These decisions consisted of a choice between allocating experimental investment units to either an option with an uncertain return or second option with a certain return. Following the factorial design, these decisions were taken under one of the following treatment combinations, (1) risk and no trade, (2) ambiguity and no trade, (3) risk and trade, or (4) ambiguity and trade. Table 1 summarizes the experiment design.

Table 1 Experiment design

	Without trade	With trade
Risk	37 individuals[5] 5 investment decisions	4 market sessions (10 subjects in each) 5 trading periods and investment decisions
Ambiguity	40 individuals 5 investment decisions	4 market sessions (10 subjects in each) 5 trading periods and investment decisions

[5] Forty subjects participated but data was not recorded for three subjects due to a computer error.

Sixty-three different subjects participated in the experiment. Subjects were students of Griffith University in Brisbane, Australia. Experiments ran for approximately two hours beginning with procedures to measure preferences, and followed by instructions and a short quiz to check subjects' comprehension of the instructions[6]. Participants also answered a brief questionnaire of demographic questions. Section 4.1 outlines the experimental procedures used to measure preferences and Section 4.2 describes the procedures used to compare investment decisions.

4.1. Experimental procedures for measuring preferences

A number of different procedures for measuring risk and ambiguity preferences were used[7]. These methods were a paired lottery choice procedure based on the experiment of Holt and Laury (2002), certainty equivalent procedures, a Becker-DeGroot-Marschak (BDM) procedure[8] for measuring certainty equivalents for both risky and ambiguous lotteries, a lottery choice procedure for measuring 'prudence' (a property of the third derivative of the utility function), and a probability equivalence procedure for measuring ambiguity preferences[9], similar to the method used by Lauriola and Levin (2001). Each of the methods used in this study are briefly described below.

Each subject was presented with a list of paired lotteries such that the point a subject crosses over from choosing a low-risk lottery to choosing a high-risk lottery could be used to infer their degree of risk aversion. The probability of receiving a higher payoff

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[6] For a copy of the instructions see http://www.ens.gu.edu.au/Johnt/papers/instructions.zip
[7] Measurement procedures were programmed and conducted with the software zTree (Fischbacher, 1999).
[8] See Becker *et al*. (1964) for detail.
[9] This type of preferences under ambiguity measured by this type of probability equivalence method have been described mathematically and referred to as 'imprecision aversion' by Gajdos *et al*. (2006).

from both the low and high-risk lotteries increases down the list until the expected value of the high-risk lottery exceeds that of the low-risk lottery. Preferences over potential gains and losses were measured with this procedure[10].

Certainty equivalents were inferred from the point a subject crossed-over from choosing a binary lottery to a list of certain amounts. Certainty equivalents were measured for a lottery with a 50 percent chance of a $20 payoff and a 50 percent chance of a $0 payoff for both gains and losses, and for a similar lottery with payoffs of $8 or $0[11]. For the lotteries with the possible $20 gain or loss the procedure was iterative with seven iterations for gains and three iterations for losses.

A certainty equivalent was also used to test whether subjects were 'prudent'. Prudence is defined as a positive third derivative of the utility function or alternatively, as a preferences for attaching an additional mean-preserving variance to the better outcome of a lottery. This test serves as a test of appropriateness for testing predictions about behaviour that might depend on particular functional forms of utility functions when using the relatively low payoffs common in experiments. This test was based on the procedure developed by Tarazona-Gomez (2004). Certainty equivalents were measured for one lottery with additional variance attached to the higher payoff of a simple lottery and for a second lottery with this variance attached to the lower payoff of the same lottery.

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[10] Rather than measuring preferences using purely hypothetical choices, preferences were measured over a range of payoffs equivalent to earnings from a typical economic experiment, with one choice from each subjects selected for actual payment. This meant that subjects could experience losses as well as gains because payoffs were subtracted or added to payments at the end of the session.

[11] A fifty-percent probability has been shown to minimize response biases (Tversky and Wakker, 1995).

Two different procedures based on the Ellsberg (1961) two-colour problem were used to measure ambiguity preferences over lotteries, with a return of $20 for drawing an orange marble and a $0 return for drawing a black marble. The first procedure used the BDM mechanism to elicit subjects' values for a draw from an urn with a known probability of return compared with a draw from an urn with an unknown probability of return. In the second procedure, subjects were presented with a list of choices between an urn with an unknown composition and an urn with a known composition of marbles. With 0 orange marbles and 50 black marbles at the start of the list, the number of orange marbles was steadily increased down the list, ending with 50 orange marbles and 0 black marbles. The crossover point from choosing the urn with an unknown proportion to choosing the urn with the known proportion was used to infer ambiguity preferences.

4.2. Experimental procedures for investment decisions and market interactions

The procedures used to compare the investment decisions under the treatments of risk and ambiguity, with and without trade, consisted of a repeated portfolio choice type of decision and a multiple-unit double auction market. Under conditions of risk, subjects were provided with information about the probability of return from the uncertain investment option. Under conditions of ambiguity, subjects were not provided with this information. Trading periods lasted for three minutes and one minute was allowed for each investment decision.

A portfolio choice problem was chosen as the framework for the investment decisions because it provides a suitable decision framework for studying both investment

decisions and trade in investment units (see Eeckhoudt *et al*., (2005) for a theoretical treatment). Subjects were initially allocated 100 investment units at the start of each decision period and then could vary their exposure to risk by investing in either (A) an uncertain option with a payment of either 8 cents or 0 cents per investment unit of (B) a certain option with a payment of 2 cents per unit[12]. The realization of the uncertain option was independent for each subject in order to maximize the amount of information available in the market sessions.

In market sessions, subjects had the opportunity to trade investment units before the investment decisions. Each market consisted of 10 subjects. All subjects had an identical initial endowment of 100 investment units. The number of units each subject could usefully invest was restricted to 200 units. However, in order not to restrict any potential arbitrage role of the market, a subject could buy units in excess of their maximum use even though these units did not have any value to subjects after the market closed.

The choice of a multiple-unit double auction trading institution is a key part of the experiment design as these institutions potentially provide more feedback to market participants than alternatives like sealed-bid auctions (see, for example, Smith *et al*., 1982)[13]. Subjects submitted offers consisting of a price and a quantity. All or part of this quantity may be traded to an offer on the opposing side of the market with a matching price leaving the remaining quantity on offer as the outstanding offer. In the

[12] In the experiments the options were framed to subjects in the context of an irrigation decision. In the scenario water could either be allocated to Crop A (which would either be successfully grown and sold or unsuccessful) or to Crop B (which would always be grown and sold successfully). This context is similar to the context of many other experiments conducted at Griffith University which also aided in the explanation of decision tasks to subjects.

experimental markets, offers were required to meet a bid-ask spread reduction rule and superseded offers were displayed until the market cleared. Information about the history of bids and transactions was available until the end of the session. Any subject could participate in the market as a buyer or a seller or both. Each trading period lasted for three minutes. This was followed by a one minute investment decision period.

5. Results

Preferences in decision-making under risk and ambiguity are presented first in Section 5.1. This is followed by a comparison of measured preferences with the direction of trades in the double auction in Section 5.2. The results section concludes with an analysis of the effect of ambiguity and market interactions on individual investment decisions in Section 5.3.

5.1. Preferences in decision-making under risk and ambiguity

The summary statistics (medians, means and standard deviations) of each preference measurement procedure are presented in Table 2. The parameters for exponential and power utility functions were estimated using non-linear least squares based on the seven iterations of the iterative certainty equivalent (ICE) procedure for the $20 or $0 lottery over gains. The "BDM ratio" is the ratio of the WTA for the known urn to the WTA for the unknown urn.

[13] See Plott and Gray (1990) for a detailed description of the multiple-unit double auction.

Table 2 Summary statistics (medians, means and standard deviations) of responses for each preference measurement procedure

Procedure	Median	Mean	Standard deviation
Paired lottery (gains)*	6.00	5.39	1.62
Paired lottery (losses)*	6.00	6.42	1.90
CE (gains, $20/$0)^	$10.00	$10.16	$3.81
CE (losses, $20/$0)^	$-9.40	$-9.35	$3.58
CE (gains, $8/$0)^	$3.92	$3.78	$1.49
ICE (gains, exponential)[#]	0.0496	0.0496	0.3109
ICE (gains, power)[#]	0.983	1.0155	0.1878
BDM (risk, $20/$0)^	$10.00	$10.01	$5.01
BDM (ambiguity, $20/$0)^	$8.00	$8.95	$5.68
BDM ratio[$]	1.20	1.36	0.49
Prob. Equiv. (ambiguity)[##]	42.00%	40.76%	14.46%

* The level of risk-aversion is measured on a scale of 1 to 11, where 1 is the most risk-averse, 6 is risk-neutral and 11 is the most risk-loving. ^ These values are certainty equivalents or WTA measurements. [#] For the exponential function, a value less than 0 is risk-loving, 0 is risk-neutral and greater than zero is risk-aversion. For the power function, a value greater than 1 is risk-loving, 1 is risk-neutral and less than 1 is risk-aversion. [$] A value of this ratio greater than 1 indicates ambiguity-aversion, 1 is ambiguity-neutral and less than 1 is ambiguity-loving. [##] These values reflect the probability at the point a subject switched to choosing the Ellsberg urn with a known probability.

The median and mean values for the paired lottery choices, the certainty equivalents, and BDM procedure for risk preferences are close to the risk-neutral responses. The BDM ratio and probability equivalence procedures reveal mean responses consistent with ambiguity-aversion. There is a low level of agreement between all the measures of preference under risk and ambiguity. To test the level of agreement between the different measurements, the rankings of subjects' preferences by each procedure was compared. The level of agreement amongst the different procedures was low but significant (Kendall's coefficient of concordance, $W = 0.18$, $p < 0.005$). This was anticipated as many previous attempts to relate risk and ambiguity, for example, have been affected by unreliable measurements (Camerer and Weber, 1992). Subjects' preferences were generally poorly correlated and only some measurement procedures

are significantly correlated. Table 3 displays the correlation coefficients for the procedures are significantly correlated.

Table 3 Correlations between the alternative preference measurement procedures.

Pearson Correlations		CE (gains, $20/$0)	CE (losses, $20/$0)	CE (gains, $8/$0)	BDM (risk, $20/$0)	ICE (gains, exponential)
CE (gains, $8/$0)	Correlation Coefficient	**.463(**)**		1		
	Sig. (2-tailed)	.000				
BDM (ambiguity,$20/$0)	Correlation Coefficient	**.359(**)**		**.320(*)**	**.731(**)**	
	Sig. (2-tailed)	.004		.011	.000	
Paired lotteries (gains)	Correlation Coefficient		**-.298(*)**	**.268(*)**		
	Sig. (2-tailed)		.018	.034		
Paired lotteries (losses)	Correlation Coefficient		**.305(*)**			
	Sig. (2-tailed)		.015			
Probability Equivalence (ambiguity)	Correlation Coefficient	**.249(*)**				
	Sig. (2-tailed)	.049				
BDM ratio	Correlation Coefficient	**.268(*)**				
	Sig. (2-tailed)	.033				
ICE (gains, exponential)	Correlation Coefficient	**.665(**)**		**.435(**)**		1
	Sig. (2-tailed)	.000		.000		
ICE (gains, power)	Correlation Coefficient	**.745(**)**		**.444(**)**		**.922(**)**
	Sig. (2-tailed)	.000		.000		.000

* significant at alpha = 0.05; ** significant at alpha = 0.01

The correlation coefficients that are significant are in the direction anticipated. For example, there is a positive correlation between the $20/$0 and $8/$0 CE responses for gains (Pearson correlation, $r = 0.463$, $p < 0.01$), there is a significant negative correlation between the $20/$0 CE response over losses and the paired lottery response over gains (Pearson correlation, $r = -0.298$, $p < 0.05$), and a significant positive correlation between the $20/$0 CE response over losses and the paired lottery response over losses (Pearson correlation, $r = 0.305$, $p < 0.05$).

Preferences measured under conditions of ambiguity using the BDM procedure are significantly correlated with preferences elicited under conditions of risk for the BDM

procedure (Pearson correlation, $r = 0.731$, $p < 0.01$), the \$20 or \$0 lottery CE (Pearson correlation, $r = 0.359$, $p < 0.01$) and the \$8 or \$0 CE (Pearson correlation, $r = 0.320$, $p < 0.05$). Likewise, there is a significant correlation between the \$20 or \$0 lottery CE responses and the probability equivalence measure of ambiguity-preferences (Pearson correlation, $r = 0.249$, $p < 0.05$) and the BDM ratio measure of ambiguity-preferences (Pearson correlation, $r = 0.268$, $p < 0.05$). These results provide evidence for a positive relationship between risk preferences measured under conditions of risk and ambiguity and a positive relationship between risk preferences and ambiguity preferences.

Table 4 and Table 5 present the results for the iterative certainty equivalent procedure for gains and losses, respectively. The high and low values for each binary lottery, their respective levels of utility are displayed together with the mean, median and standard deviations of the certainty equivalents that were observed. The certainty equivalents corresponding to a risk neutral response are provided for comparison.

Table 4 Results of the iterative certainty equivalent procedure for gains.

Measurement	Lottery ($)		Expected Utility	Risk neutral certainty equivalents ($)	Observed certainty equivalents ($)		
x_i	x_l	x_h			Mean	Median	Std. Dev.
1	0	20	0.5	10	10.59	10.00	4.67
2	0	x_1	0.25	5	5.50	5.00	3.87
3	x_1	20	0.75	15	14.29	15.00	4.66
4	0	x_2	0.125	2.5	3.26	2.59	3.28
5	x_2	x_1	0.375	7.5	8.36	7.50	4.77
6	x_1	x_3	0.625	12.5	12.83	12.91	4.86
7	x_3	20	0.875	17.5	16.72	17.80	3.94

Table 5 Results of the iterative certainty equivalent procedure for losses.

Measurement	Lottery ($)		Expected Utility	Risk neutral certainty equivalents ($)	Observed certainty equivalents ($)		
x_i	x_l	x_h			Mean	Median	Std. Dev.
1	0	-20	-0.5	-10	-9.39	-9.40	4.30
2	0	x_1	-0.25	-5	-5.14	-4.80	3.83
3	x_1	-20	0.75	-15	-13.77	-14.29	3.44

Exponential and power utility functions were fitted to the data for gains following the methodology of Smidts (1997). These parameters and the results of the other measurement procedures were used to examine the heterogeneity subjects' risk preferences. Subjects were classified into the categories of risk-preferring, risk-neutral and risk-averse for each procedure. The results of this classification are presented in Table 6.

Table 6 Number of subjects in each category of risk preference for each procedure

Procedure	Risk-preferring	Risk-neutral	Risk-averse	Other[14]
Paired lotteries (gains)	8	20	28	7
Paired lotteries (losses)	23	15	19	6
CE (gains, $20/$0)	28	7	27	1
CE (losses, $20/$0)	37	3	21	2
CE (gains, $8/$0)	21	11	29	2
ICE (gains, exponential)	28	2*	31	2^
ICE (gains, power)	33	2*	26	2^
BDM (risk, $20/$0)	24	14	25	0
BDM (ambiguity, $20/$0)	33	12	18	0

* Two subjects responded to all iterations of the certainty equivalent procedure as risk-neutral. ^ The non-linear least squares could not fit curves to another two subjects.

Because risk preferences were elicited using the paired lottery choices and the $20 or $0 CE for both gains and losses, the data can be used to test the predictions of prospect theory, that individuals will be risk-averse over gains and risk-seeking over

[14] Subjects were classified as "other" if their choices violated the salience assumption, for example, by indicating a preference for a lower certain amount instead of a higher certain amount in the list of paired lottery choices. This is most likely due to some misunderstanding of the instructions.

losses (Kahneman and Tversky, 1979). Based on the paired lottery choice procedure, thirteen subjects were classified as risk-averse over gains as well as risk-preferring over losses. This proportion was significantly greater than the proportion expected by chance alone (chi-square test, $\chi^2 = 9.188$, $p < 0.005$)[15]. Similarly, the proportion of subjects following this pattern of responses in the certainty equivalent procedures was also found to be significantly greater (chi-square test, $\chi^2 = 14.697$, $p < 0.001$). These two results indicate that the proportion of subjects following the pattern described by prospect theory is significantly greater than predicted by chance alone.

The values of the BDM ratio and the probability equivalence procedures for assessing ambiguity preferences were used to classify subjects into similar categories. The results are presented in Table 7.

Table 7 Classification of subjects into each category of preference based on the BDM and probability equivalence procedures.

Category	BDM ratio	Prob. Equiv.
	Number	Number
Ambiguity-averse	31	44
Ambiguity-neutral	22	10
Ambiguity-preferring	10	8
Other	0	1

More subjects were classified as ambiguity-averse based on the probability equivalence procedure than the BDM ratio. Because the number of subjects who are ambiguity-preferring is similar for both procedures, this appears to be due to the greater number of subjects classified as ambiguity-neutral based on the BDM ratio. Twenty-two subjects responded with the same WTA for both the known and unknown

[15] In other words, the observed proportion was compared with the proportion expected if all subjects were equally likely to fall into any category under gains as they were under losses.

urns whereas only ten subjects switched over from choosing the urn with unknown probabilities to choosing the known urn at the probability of fifty-percent corresponding to an ambiguity-neutral preference.

The mean WTA for the known lottery was significantly greater than the mean WTA for the unknown lottery (t-statistic = 3.577, $p < 0.05$). Likewise, the mean response from the probability equivalence procedure was significantly different from the mean probability of fifty percent consistent with an ambiguity-neutral decision-maker (t-statistic = 5.211, $p < 0.01$). This suggests that the mean preferences for an uncertain option under conditions of ambiguity will be lower than expected if ambiguity-neutral decision-makers were assumed.

Hypothesis 1: Subjects will have heterogeneous preferences over risk and ambiguity for the level of incentives used in the experiment.

Given the range of risk and ambiguity preferences reported above, the hypothesis that subjects will have heterogeneous preferences over the range of payoffs commonly used in economic experiments is supported by the analysis. Even though the correlation amongst alternative measures is low, the results demonstrate that subjects respond differently to the risks and ambiguities associated with these levels of incentive. However, observing risk-aversion over these relatively small payoffs may imply very extreme risk attitudes for larger stakes.

Cox and Sadiraj (2006) noted that this is a consequence of any decision theory that uses concave transformations of positive money payoffs, including expected utility

theory and cumulative prospect theory. It may be that whilst heterogeneous risk attitudes are observed over the level of payoffs commonly used in economic experiments this behaviour many not be best described by risk preferences caused by a diminishing marginal utility of wealth function as discussed by Rabin (2000).

This interpretation is supported by the lack of evidence for ‘prudence’. The pattern of preferences over lotteries predicted by a positive third derivative of the utility function was not observed. Subjects did not generally display a preference for attaching an additional mean variance to the lower outcome of a binary lottery, as predicted by prudence, a positive third derivative of the utility function. Instead, significantly higher certainty equivalents for the opposite choice were found (t-statistic = 2.57, $p < 0.05$). This adds additional weight to the interpretation that whilst subjects respond to the uncertainties associated with the incentives afforded in the experiments, the advantages of describing subjects’ preferences in terms of the precise curvature of utility functions may be limited.

5.2. A comparison of measured preferences with the direction of trades in the double auction

The direction of trade consistent with measured preferences was compared with the observed direction of each transaction in the market. Table 8 displays the number of trades that the measured preferences predicted in the right direction, the wrong direction, trades that occurred between subjects with the same measured preference,

and trades for which at least one subject had a missing value[16]. The results of Chi-square tests that were used to test the significance of these comparisons are also reported in Table 8.

Table 8 The proportions of trade and tests of the number of trades predicted accurately in the right direction by each assessment of risk and ambiguity preferences.

	CE (gains, $20/$0)	CE (losses, $20/$0)	CE (gains, $8/$0)	ICE (gains, exponential)	ICE (gains, power)	BDM (risk, $20/$0)	BDM (ambiguity, $20/$0)	BDM ratio	Paired lotteries (gains)	Paired lotteries (losses)	Prob. Equiv. (ambiguity)
Right direction	.41	.54	.34	.54	.56	.62	.62	.54	.27	.30	.43
Wrong direction	.19	.29	.29	.43	.44	.33	.35	.38	.29	.16	.47
Same measure	.22	.02	.01	.02	.00	.05	.02	.09	.16	.12	.10
Missing measure	.17	.15	.36	.00	.00	.00	.00	.00	.29	.42	.00
Chi square	**25.258(**)**	**25.801(**)**	1.108	**3.889(*)**	**4.738(*)**	**29.590(**)**	**24.662(**)**	**9.197(*)**	.140	**13.620(**)**	.585
Sig. (p value)	.000	.000	.292	.049	.029	.000	.000	.002	.709	.000	.444

* significant at alpha = 0.05; ** significant at alpha = 0.01

The majority of these comparisons (8 out of 11) significantly predicted the direction of transactions in the right direction more often than in the wrong direction. Whilst both the $20 or $0 CE for gains and losses predicted trades correctly, of the two paired lottery choice procedures only the responses for losses predicted more trades correctly than incorrectly. Notably, both the BDM measures of risk preferences predicted more trades correctly, as did the ratio between the BDM measures for the known and unknown lotteries. However, the probability equivalence measure of ambiguity preferences did not.

[16] This occurred when a subject answered a question indicating they would prefer to receive nothing rather than the chance of a higher payoff. This suggests the subject did not understand the instructions for this procedure.

Hypothesis 2: Trade will be observed in the direction from subjects with lower certainty equivalents and measured preferences for risk and ambiguity to subjects with relatively higher certainty equivalents or measured preferences.

The evidence indicates that the level of incentives is sufficient to motivate trade in the direction predicted, from subjects with a lesser risk or ambiguity preferences for the investment units towards subjects with a greater risk or ambiguity preference. The next section presents the results on the effect of ambiguity and market interactions on individual investment decisions.

5.3. The effect of ambiguity and market interactions on individual investment decisions

Descriptive statistics are presented first followed by the results of a mixed model analysis of the effect of the information about the probability and market trade on the proportion of investment units allocated by subjects to the uncertain option in each decision period. Table 9 presents the means and standard deviations of the proportion invested in the uncertain option for each treatment combination.

Table 9 Summary of individual investment decisions – % allocated to the uncertain option

Treatment	Mean	Standard deviation
Decisions under conditions of risk	78.0	25.9
Decisions under conditions of ambiguity	67.8	26.7
Decisions under conditions of risk in markets	85.7	18.8
Decisions under conditions of ambiguity in markets	76.8	28.4
Grand mean under all conditions	73.5	29.8

The grand mean of the percentage allocated to the uncertain option by subjects was 73.5 percent with a standard deviation of 29.8. The relative magnitude of contributions is in the direction predicted by theory with the highest contributions observed under conditions of risk and a market (85.7 percent) and the lowest contributions under conditions of ambiguity without a market (67.8 percent). This pattern is also evident in Figure 1 below, which displays the mean contributions over time for each treatment combination.

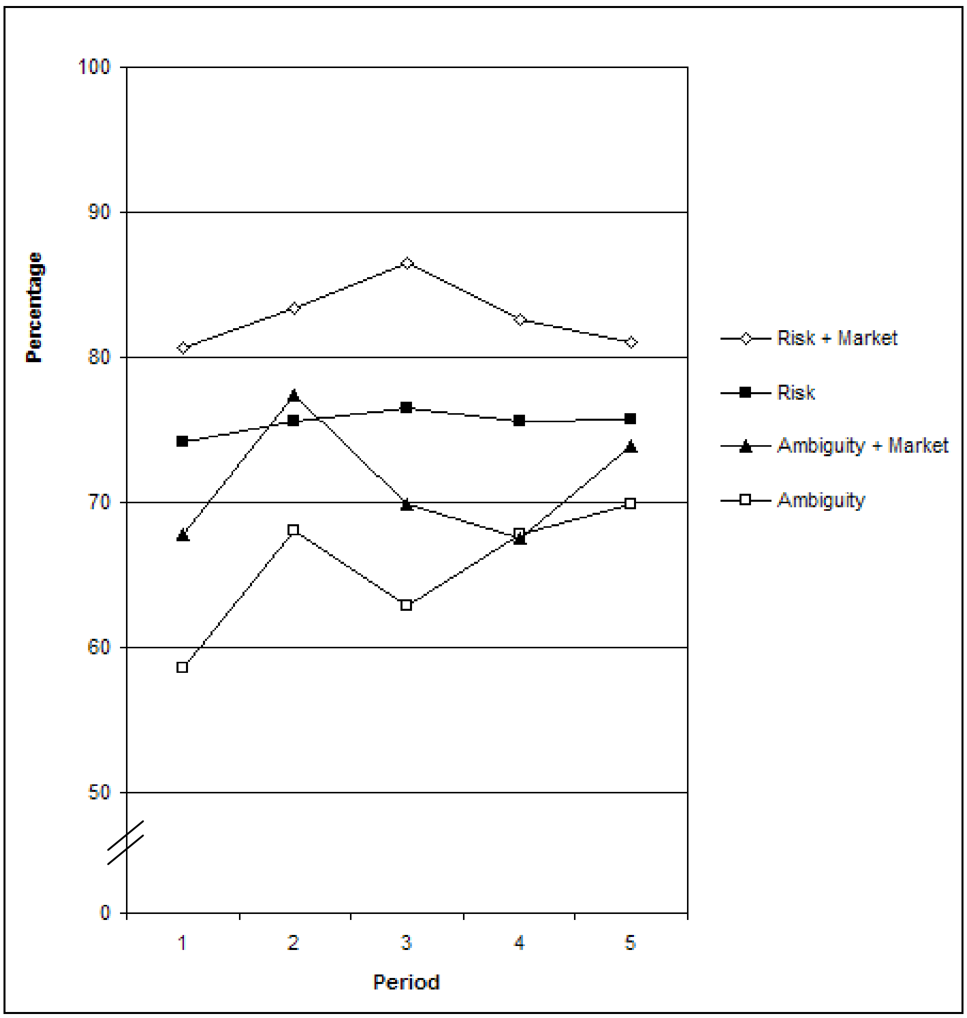

Figure 1 Mean contributions to the uncertain investment option in each decision period for each treatment combination

Statistical analysis of treatment effects was performed in SPSS v. 14 (SPSS, 2005) using a mixed model analysis of the proportion of contributions to the uncertain option in the investment decision. The data was first transformed using an arcsine transformation. An ARMA(1,1) model was selected based on comparisons of alternative covariance structures for the repeated measures, including an unstructured and a compound symmetric covariance using Akaike's Information Criterion, Schwarz' Bayesian criterion and likelihood ratio tests[17]. Table 10 summarises the results of the mixed model analysis.

Table 10 Results of the mixed model repeated measures analysis with an ARMA(1,1) covariance structure

Source	Numerator df	Denominator df	F	Significance
Intercept	1	151.540	840.407	.000
Information	1	151.540	7.004	.009
Market	1	151.540	4.036	.046
Period	4	283.206	2.225	.067
Information * Market	1	151.540	.011	.918
Information * Period	4	283.206	.839	.501
Market * Period	4	283.206	.351	.843
Information * Market * Period	4	283.206	.225	.924

The effect of the market on contributions to the uncertain investment option was significant ($p = 0.046$) as was the effect of providing information about the probability of the uncertain investment option ($p = 0.009$). Contributions to the uncertain investment option did not change significantly between the periods ($p = 0.067$). None of the potential interactions between treatment effects was significant in the statistical model.

[17] The unstructured model fits the covariance structure significantly better than the compound symmetric model ($\chi^2_{13\text{ d.f.}} = 30.02$; $p < 0.01$). The unstructured model does not fit the covariance structure significantly better than the ARMA(1,1) ($\chi^2_{12\text{ d.f.}} = 13.852$; $p > 0.05$).

Hypothesis 3: Effect of risk and ambiguity

The results support the hypothesis that the mean proportion of investment units allocated to the uncertain investment option was significantly higher under conditions of risk than under conditions of ambiguity (p = 0.009). Pooling the mean contributions across the market and non-market sessions gives mean contributions from subjects of 79.1 percent of their initial endowments under risk compared with 68.2 percent under conditions of ambiguity.

Hypothesis 4: Effect of market trade

The results support the hypothesis that a greater proportion of investment units would be invested in the uncertain option with trade than without trade (p = 0.046). Pooling the mean contributions across the risk and ambiguity sessions gives mean contribution from subjects in trade sessions of 77.1 percent compared with 70.3 percent without trade (p = 0.046).

Hypothesis 5: Interaction of treatment effect

The results do not support the hypothesis that the market would eliminate the effect of ambiguity on investment decisions. The hypothesized interaction between market treatment and information treatment was not statistically significant (p = 0.918), although the difference in mean contributions was in the direction predicted. A greater difference in contributions was observed in the non-market treatment compared with the market treatment (contributions were 15 percent higher under risk than ambiguity in the non-market treatment compared with 11 percent higher in the market treatment).

6. Discussion and conclusions

The results of this study suggest that ambiguity-aversion in individual decisions persists even with the power of market feedback. Experiments were designed so that individual decisions could be compared under conditions of risk and ambiguity, with and without trade in a market. A computerized double auction market provided traders with a great deal of feedback and opportunities for learning. Although information about probability and market trade increased individuals' willingness to invest in an uncertain prospect, this study found no evidence to suggest that market interactions could eliminate ambiguity-aversion in individual decisions. Whilst previous experiments have shown an effect of ambiguity on market behaviour (Sarin and Weber, 1993), past results can be partly explained by the Comparative Ignorance Hypothesis (Fox and Tversky, 1995). The results of the present study, with separate decision environments for risky and ambiguous choices, suggest that markets are unable to eliminate the effect of ambiguity on individual decisions, even without a comparative context.

In addition to these main findings, this study has compared a variety of procedures for measuring risk and ambiguity preferences. These measurements were compared with the direction of each transaction in the double auction markets. The majority of the procedures tested produced results consistent with trade from subjects with lower preferences for risk and ambiguity to subjects with higher preferences. Measurements indicate that although mean responses were fairly close to the values expected for risk-neutral and ambiguity-neutral decision-makers, subjects' exhibited a broad range of preferences. The subject pool exhibits risk-aversion, risk-neutrality and risk-seeking behaviours as well as ambiguity-aversion, ambiguity-neutrality and

ambiguity-seeking behaviours. Notably, a significant proportion of subjects exhibited the pattern of behaviour predicted by prospect theory, with risk-aversion over gains and risk-seeking over losses (see Di Mauro and Maffioletti, 2004). Where significant correlations amongst different measures were observed they were in the expected direction. In particular, preferences elicited using the BDM mechanism for risk and ambiguity were highly correlated. Risk preferences elicited for a lottery over potential gains of $20 or $0 were also significantly correlated with ambiguity preferences, measured using both the ratio of responses under risk and ambiguity from a BDM mechanism, and a probability equivalence measure. This provides additional support to the finding by Lauriola and Levin (2001) that risk and ambiguity preferences are positively correlated.

However, the level of agreement amongst the different procedures was low, so perhaps it is inadvisable to rely upon any single measurement of risk or ambiguity preferences. Additionally, the work of Rabin (2000) and Cox and Sadiraj (2006) suggested that the preferences observed for some subjects over relatively small amounts imply quite extreme preferences over larger amounts. It may be inappropriate to describe risk preferences over small amounts of experimental rewards in terms of particular functional forms of the utility function. Subjects were not found to be 'prudent', a preference determined by a positive third derivative of the utility function, which adds additional weight to this interpretation.

Measured risk and ambiguity preferences were used to examine the direction of each transaction in the experimental markets. The majority of the different procedures used to assess risk and ambiguity preferences predicted trades in the observed direction

more often than in the opposite direction. The ability to make this comparison was confirmed as a particular advantage of using the double auction in market experiments. These comparisons might help guide the choice of procedures for measuring risk and ambiguity preferences in future research.

The findings of this study have important theoretical and applied implications. Buschena (2003) noted that many individual decision experiments demonstrate violations of expected utility theory without including the market feedback essential to Friedman's (1953) discussion of the rationality assumption. These new results show that ambiguity-aversion can persist even with the power of market feedback. This study therefore contributes additional empirical evidence to this ongoing theoretical debate. If ambiguity persists in individual decisions even in the presence of the market feedback and opportunities for learning provided by the computerized double auction market, then it is likely that ambiguity-aversion will persist in other types of market institution as well. Blaug (1992) suggested a trade-off exists between the mathematical rigor achieved by models making strong behavioural assumptions and their relevance. So, rather than rejecting subjective expected utility theory, this study highlights the importance of selecting behavioural assumptions to suit each purpose.

The choice of behavioural assumption therefore depends on the purpose of analysis. Berg (2003) argued that basing policy analysis on a variety of methodological approaches would diversify the risk of error. This logic suggests that robust policies can be designed by evaluating alternatives using a number of alternative behavioural assumptions. In the arena of agricultural and environmental policy analysis, risk and

uncertainty are central considerations, especially with the introduction of new markets for water resources and emissions permits. Epstein and Wang (1994) demonstrated the potential consequences of interactions between ambiguity-averse decision-makers in markets. This study has shown that ambiguity-aversion persists in individual decisions even with the power of market feedback. Ambiguity-aversion is perhaps particularly important when evaluating alternative policies for agricultural and environmental markets.

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