ABSTRACT. Heath and Tversky (1991, Journal of Risk and Uncertainty 4:5–28) posed that reaction to ambiguity is driven by perceived competence. Competence effects may be inconsistent with ambiguity aversion if betting on own judgement is preferred to betting on a chance event, because judgemental probabilities are more ambiguous than chance events. This laboratory experiment analyses whether ambiguity affects prices and volumes in a double auction market, and contrasts ambiguity aversion to competence effects. In order to test for the presence of competence effects, in the experiment uncertainty is tied to the realisation of events about which the decision maker is more or less knowledgeable. Two experiments are presented: in the first, knowledge is exogenous, whereas in the second the knowledge judgement is endogenous. Market prices provide evidence in favour of the competence hypothesis only when competence is self-assessed. Comparable volumes are observed in both experiments.

KEY WORDS: ambiguity, competence, double auction, experiments, markets

JEL CLASSIFICATION: D81, C91

1. INTRODUCTION

Theoretical research built on the seminal paper by Schmeidler (1989) has shown that in asset markets vague state probabilities may lead to price volatility, trading inertia and may worsen risk-sharing efficiency if traders are ambiguity averse (see Dow and Werlang, 1992; Epstein, 2000; Epstein and Wang, 1994; Mukerji and Tallon, 2001, 2003). Thus, with non-expected utility traders, there are grounds for expecting ambiguity (Ellsberg, 1961) to impact upon market equilibria.
This theoretical result contrasts with the standard neoclassical argument according to which markets should eliminate behavioural biases with respect to the normative model (Camerer, 1987), including ambiguity effects. This claim is based on the idea that in markets individuals repeatedly face the same decisions, receive adequate incentives and obtain feedback from other traders and market prices.

As a matter of fact, there is evidence that some violations of expected utility theory, such as preference reversal (Cox and Grether, 1996) and the WTP-WTA disparity (Loomes et al., 2003) are reduced in market settings. However, most of the evidence gathered on ambiguity aversion refers to individual decision making settings (Camerer and Weber, 1992), whilst only a few market experiments study ambiguity. Since these experiments provide mixed evidence (Camerer and Kunreuther, 1989; Di Mauro and Maffioletti, 2001, 2004; Sarin and Weber, 1993), there are reasons for investigating the issue of ambiguity effects in markets further.

This paper presents an economic experiment designed to test whether ambiguity aversion arises and persists in markets. The specific research question which is addressed is whether ambiguity aversion is reflected in prices and exchange volumes. Compared to the existing experimental literature, the experiment innovates in two respects. First, ambiguity is made operational as natural event uncertainty, rather than by means of chance processes such as second order probabilities or Ellsberg's urn. This permits to test whether the weak ambiguity effects found in some experimental markets are due to the adoption of a weaker form of uncertainty. In turn, the use of real event uncertainty allows for the search of effects on valuation tied to the decision maker's perceived knowledge of the uncertain event, such as in Heath and Tversky (1991)'s competence hypothesis. Second, the experimental design allows for pricing predictions which are independent of both risk and ambiguity attitudes (Rietz, 1999; Weber et al., 2000). This imposes a market discipline on prices which is not simply derived from generic feedback and experience which
could be gained also in non market settings (Loomes et al., 2003).

The market institution selected is a standard computerised double auction, run for a series of repetitions in which both event bets and comparable chance bets are traded.

The argument is set in four sections. The first discusses ambiguity aversion in experimental markets. The second presents the hypotheses tested, the experimental design and the organisation of the experimental market. Section 4 analyses the experimental data. Section 5 concludes with a discussion of results and of their implications for the operation of markets, and for research in decision making under ambiguity.

2. AMBIGUITY ATTITUDE, COMPETENCE AND MARKETS

2.1. Some explanations of ambiguity

The paradigmatic example of ambiguity aversion is Ellsberg’s two-colour experiment. Confronted with an urn containing 100 red and black balls in a ratio totally unknown to the decision maker (the ambiguous urn), and an urn with 50 red and 50 black balls (the risky urn), the decision maker prefers to bet on the latter whatever the colour, thus implying that probabilities cannot be inferred from choice.

Following Ellsberg, in choice tasks ambiguity aversion is defined as the decision maker’s preference to bet for and against a chance event whose probability is known, rather than on an equivalent event with vague probabilities. In valuation settings, given bets with non-negative payoffs, an ambiguity averse decision maker’s sum of certainty equivalents for and against a chance bet exceeds the sum of certainty equivalents for a comparable ambiguous bet.

Ambiguity attitude has been attributed either to cognitive or motivational factors (Rode et al., 1999). Ellsberg (1961) says that ambiguity is “a quality depending on the type, amount, reliability and ‘unanimity’ of information, and giving rise to one’s degree of ‘confidence’ in an estimate of
relative likelihoods” (p. 657). Frisch and Baron (1988) ascribe ambiguity aversion to the fact that the decision maker lacks the knowledge about some aspects of the stochastic structure of a problem that are unknown but could be known. Some authors have posited that reaction to ambiguity is part of a more general phenomenon, which has been called source dependence. Preferences depend “not only on the degree of uncertainty but also on the source of uncertainty” (Tversky and Wakker, 1995, p. 1270). In particular, preference patterns in Ellsberg’s experiment, i.e. the preference to bet for and against any event in the known urn rather than for any of the events in the ambiguous urn, can be defined as the preference for one source of uncertainty over another. The preference for a “source” determines the representation of the decision problem and, hence, it influences preferences amongst alternative prospects.

Heath and Tversky (1991) tie preference for one source of uncertainty to perceived competence about that source. Individuals prefer to “bet on their own judgement over an equiprobable chance lottery when they consider themselves knowledgeable, and on the chance lottery when they feel ignorant” (Heath and Tversky, 1991, p. 11). In pricing tasks, the competence hypothesis implies that for high/low competence events the sum of certainty equivalents for and against the event is higher/lower than the sum of certainty equivalents for an equivalent chance event. Competence effects are inconsistent with ambiguity aversion, because judgemental probabilities are more ambiguous than chance events. Fox and Tversky (1995) find that the feeling of competence may be enhanced by choice/valuation in a comparative setting in which the decision maker is made to feel more knowledgeable about one source than about another.

2.2. Markets with ambiguity averse traders: theory

A number of extensions of the classical Bayesian model admit the Knightian distinction between risk and uncertainty, and the implications of reaction to ambiguity for asset markets
have been explored in a growing number of papers (amongst others, Dow and Werlang, 1992; Epstein, 2000; Epstein and Wang, 1994; Mukerji and Tallon, 2001, 2003). Some of these results, concerning trades, prices and portfolios are shortly reviewed below.

Adopting Choquet’s expected utility representation of uncertainty, Dow and Werlang (1992) present a model in which an agent operating in a static market setting with exogenously determined asset prices, and starting from a safe position, has to choose whether to hold a position in a risky asset. The authors show that with sub-additive subjective probabilities over the asset returns there will be a range of prices within which the agent will hold neither a long, nor a short position, thus identifying a continuum of equilibrium prices for which the riskless asset is the optimal choice. The maximum bid/minimum ask for the asset will depend on the agent’s perception of uncertainty and by his/her attitude towards it, and will be independent of the shape of the utility function.¹

Epstein and Wang (1994) present an infinite-horizon, multiple-asset model and show that the existence of a set of asset prices that support an optimal position is not restricted to riskless positions. More precisely, in asset markets characterised by uncertainty, equilibria may be indeterminate in the sense that for given market fundamentals there may exist a continuum of equilibrium prices: “...this leaves the determination of a particular price process to ‘animal spirits’ and sizable volatility may result” (p. 284). In the presence of Knightian uncertainty, therefore, inter-temporal price volatility may be high.

Mukerji and Tallon (2001) identify the necessary conditions under which an economy with ambiguity averse agents generates no-trade equilibria, and risk-sharing opportunities are foregone. These conditions require that: (a) there are states of the world across which assets returns vary but traders’ endowments remain identical, which implies that the risk of the asset returns is “idiosyncratic” with respect to the uncertainty tied to the agent’s income stream; (b) the risk tied to
the assets’ returns is perceived as ambiguous. Under these conditions, even if financial markets are complete, i.e. income can be transferred across all contingencies, final allocations and thus risk-sharing will be sub-optimal. So, ambiguity aversion ends up generating a form of “market incompleteness”.

2.3. *Ambiguity in markets: experiments*

There is a vast experimental literature on the relevance of ambiguity effects in individual decision making setting, but only limited and mixed evidence concerns the impact of ambiguity in markets (Camerer and Weber, 1992). Existing studies (Camerer and Kunreuther, 1989; Di Mauro, 2005; Di Mauro and Maffioletti, 2001, 2004; Sarin and Weber, 1993) exhibit different combinations of the following three design characteristics: the market institution (either semi-markets or double auctions markets); the domain of payoffs (either losses or gains); and the way ambiguity is made operational (either through second order probability distributions or the Ellsberg’s urn). Most of these studies have found that the effect of ambiguity in markets, and most notably on market prices, is weak. For instance, in Camerer and Kunreuther (1989) the object of trade was insurance coverage. The presence of ambiguity did not have any significant effect on prices but only on the number of insurance contracts that any insurer held at the end of a trading period. Sarin and Weber (1993) find that prices for risky and ambiguous assets converge when assets are traded independently, but not if exchange is simultaneous. Di Mauro and Maffioletti (2001) in a repeated English auction find that prices for risky lotteries in the loss domain converge to those for equivalent ambiguous lotteries. Di Mauro and Maffioletti (2004) find that the median ratio of ambiguous to risky bids is around one, both for gains and for losses when the probability of the chance event is 0.5.

These results may be ascribed not only to market incentives and discipline, but also to the way ambiguity is made operational. Since both second order distributions and the Ellsberg
urn are chance processes, the decision maker may learn the underlying probability distribution with market repetitions, especially when second order probabilities are involved. Thus, uncertainty generated by chance processes turns out to be less interesting than uncertainty generated by real events, and less likely to give rise to pronounced ambiguity effects. For this reason, it is crucial to investigate whether uncertainty aversion in market settings is weak when real event uncertainty is involved.\(^2\)

As far as the competence hypothesis is concerned, support in its favour has been provided both in individual choice experiments (Heath and Tversky, 1991; Kuehberger and Perner, 2003; Taylor, 1995), and in pricing tasks (Heath and Tversky, 1991, experiment 5; Keppe and Weber, 1995; Kilka and Weber, 2000).

3. THE EXPERIMENT

3.1. The hypotheses tested

Consider two single-period state contingent certificates, A and B, traded in two separate markets and whose value depends on the following chance events. A pays a liquidating dividend of 10,000 francs\(^3\) if a white ball is drawn from an urn containing 10 white and 10 black balls. No dividend is paid if black is drawn. B yields a dividend of 10,000 francs if black is drawn, and nothing otherwise. Trivially, the probability of drawing either white or black is equal to 0.5. Since A and B are complementary, i.e. perfectly and negatively correlated, an individual holding one unit of both certificates assures himself a gain of 10,000 francs. Arbitrage opportunities arise every time the sum of buying/selling prices for the two complementary certificates exceeds/is less than 10,000 francs. In efficient markets arbitrage opportunities are exploited, so that in equilibrium the sum of prices for the two certificates equals 10,000 francs, irrespective of traders’ risk attitudes.\(^4\) Next, consider two independent markets for two other certificates,
denominated C and D, whose values depend on the occurrence of a natural event, e.g. whether the temperature in a given city on a specific day is higher/lower than the historical average. Since the probability of the event is ambiguous, traders have to form subjective probabilities. Assume C/D yields a dividend of 10,000 francs if the maximum temperature in Paris (France) on July 10th is higher/lower than 20°C (the historical average), and zero otherwise. Since the liquidating value of C/D depends on a natural event, whereas the value of A/B is determined by chance, C and D are more ambiguous than A and B. However, since ownership of an equal number of C and D certificates gives a sure gain of 10,000 francs times the pairs of certificates owned, arbitrage again implies that in equilibrium the sum of prices of C and D is equal to 10,000 francs, irrespective of whether agents form subjective probabilities which differ from the objective probabilities of the chance certificates A and B.

Thus, if market participants are allowed to trade complementary certificates, arbitrage should work to eliminate price differences amongst different types of certificates. If the sum of prices for complementary certificates is below/above the certificate’s payoff, the trader should buy/dump certificates and gain a riskless profit. This leads to the following hypothesis:

Hypothesis 1A—Arbitrage pushes the sum of prices of complementary certificates to equal the aggregate payoff, irrespective of risk and ambiguity attitude.

O’Brien and Srivastava (1991), Rietz (1999), Weber et al. (2000), Di Mauro (2005) have found that arbitrage works either when professional arbitragers are involved, or after considerable experience is gained by participants in the experimental markets. If certificates C/D are perceived as more ambiguous with respect to A/B, they may trade at lower prices. Thus, an alternative hypothesis which allows for ambiguity aversion effects may be stated as follows:
Hypothesis 1B—If traders fail to recognise arbitrage opportunities, the sum of prices for complementary ambiguous certificates is lower than that for equivalent chance certificates.

Further, if preferences are affected by competence, traders will attach a higher value to certificates about which they feel more knowledgeable with respect to chance certificates. Conversely, chance certificates will trade at higher prices with respect to certificates about which traders feel incompetent.

In order to test for the presence of competence effects, in this experiment knowledge is manipulated by allowing for two types of event-based certificates: certificates whose liquidating value depends on the temperature measured in a given European capital on a particular day, and equivalent certificates concerning a US city. The markets for bets involving these events are then contrasted with the markets for chance events having comparable probabilities of occurring. Thus, allowing for competence effects, a third alternative pricing hypothesis can be stated as follows:

Hypothesis 1C—The sum of prices for higher competence certificates exceeds that for chance certificates, but chance certificates trade at higher prices than lower knowledge ones.

For illustrative purposes, consider the three couples of certificates described in Box 1.5

Pricing hypotheses 1A implies that the sum of prices of certificates A and B will be equal to that of certificates C and D and E and F, whereas hypothesis 1B entails that the sum of prices of A and B will exceed that for C and D and E and F. Conversely, the competence hypothesis requires that the sum of prices for the high competence certificates is higher than that for chance certificates, but that chance bets are valued more than low competence certificates. Taking into account that the experiment was carried out in Italy, and assuming, as done in Heath and Tversky's experiment 5 that knowledge for home cities is higher than that for foreign cities, hypothesis 1C entails that the sum of prices for C and D is higher than for
Description of certificates traded in the experiment

Certificate A—You win 10,000 francs if a white ball has been drawn from an urn containing 10 white and 10 black balls, you win zero otherwise.
Certificate B—You win 10,000 francs if a black ball has been drawn from an urn containing 10 white and 10 black balls, you win zero otherwise.
Certificate C—You win 10,000 francs if the maximum temperature in Paris on 10th July 2004 was higher than 20°C (the historic average), you win zero if it was lower.
Certificate D—You win 10,000 francs if the maximum temperature in Paris on 10th July 2004 was lower than 20°C (the historic average), you win zero if it was higher.
Certificate E—You win 10,000 francs if the maximum temperature in Missoula (USA) on 10th July 2004 was higher than 20°C (the historic average), you win zero if it was lower.
Certificate F—You win 10,000 francs if the maximum temperature in Missoula (USA) on 10th July 2004 was lower than 20°C (the historic average), you win zero if it was higher.

A and B, but that the sum of prices for A and B exceeds that for E and F.

These relationships imply that there is one proposition which discriminates between the ambiguity hypothesis and the competence hypothesis, namely the relation between the sum of prices for A and B (SUM(AB)), and for C and D (SUM(CD)). The ambiguity aversion hypothesis implies that SUM(AB) > SUM(CD), whereas the competence hypothesis entails SUM(AB) < SUM(CD). Conversely SUM(AB) > SUM(EF) is consistent with both ambiguity aversion and competence effects. Likewise, SUM(CD) > SUM(EF) is consistent with both hypotheses, provided that E–F are perceived as more ambiguous than C–D.

Unlike pricing predictions, the pattern of exchanges depends on risk attitudes: a risk averse trader perfectly hedges by holding the same number of complementary certificates, thus assuring himself a riskless payoff in all states of the world. Further, trade volumes for chance certificates may differ from
those of natural event-based certificates. As shown by Dow and Werlang (1992) and Mukerji and Tallon (2003) ambiguity averse trader have an interval of market prices at which they neither buy nor sell.

Hypothesis 2A—Chance certificates have higher trade volumes with respect to certificates which are perceived as ambiguous.

So, the sum of exchanges for A and B should exceed that for C and D, and for E and F. Further, if certificates about which traders feel more competent are perceived as less risky than those about which they feel incompetent, trade for certificates C–D will be higher than that for E–F. Huberman (2001), for instance, argues that the so called home bias in financial asset markets, that is the tendency to under-diversify the risk of the investment portfolio by giving a far larger weight to the assets of home companies with respect to foreign ones, may be grounded in a competence effect.

Hypothesis 2B—High competence certificates have higher trading volumes than low competence certificates.

Assuming again that traders consider themselves more knowledgeable about European cities than about US cities, the sum of exchanges for C and D should exceed that for E and F.

3.2. Market organisation

The market institution adopted in the experiment was a standard computerised double auction market in which eight participants traded for 12 repetitions. Prior to the beginning of the experiment subjects received oral instructions with the aid of an overhead projector on how to submit bids, asks and on how to profit from arbitraging. Two dry runs were also allowed for in order to make the participants familiar with the market procedures. Independent markets for six two-state, one-period certificates analogous to those described in Box 1
above were set up. The six certificates made up three couples of complementary bets: A and B, C and D, E and F. Assets referred to as A and B always entailed a 50% chance bet. The payoff of certificates C–F depended on the temperature in a European capital or US city on a specific day of the year.

Since the events on which the ambiguous certificates were built referred to the past, and in order to avoid the potential bias arising from the valuation of future vs. past events (Rothbart and Snyder, 1970), chance events, i.e. the drawing of either a white or a black ball to determine the payoff of certificates A–B, took place prior to the beginning of the experiment. The ball was selected by means of a computerised random draw.

At the beginning of each trading period, traders received an initial cash endowment\(^7\) and a risky position, which was defined as follows: half of the traders received two A, two C and two E certificates. The remaining half received: two B, two D and two F certificates. The initial endowment was swapped amongst participants after six periods of trading. State contingent certificates lived one period and therefore expired at the end of each market round. Traders could both sell (i.e. announce offers for) and buy (i.e. announce bids for) certificates, with the only limitation that a new bid had to be higher than outstanding bids, and a new offer had to be lower than outstanding offers. No short-selling was allowed, so certificates on hand could not be negative. Traders were remunerated on the basis of their profits in a randomly selected period, and were paid in euros a fraction of francs gained. Average earnings were € 15.00 for an hour and a half participation.

Two experiments were run for a total of 10 market sessions. Participants to all markets were Italian undergraduates from University of Catania (Italy).

– In Experiment 1 participants traded certificates whose liquidating value depended on the weather in 14 European capitals (one for each of the 12 market period plus the two dry runs) and 14 not so well-known US cities, all chosen ex ante
by the monitor. As in Heath and Tversky’s experiment 5, knowledge was exogenously assigned, i.e. it was assumed that perceived competence/knowledge of Italian students about temperatures in major EU cities was higher than that relating to US cities.

Certificates whose value depended on European weather were always denominated C and D in the experiment, whereas certificates depending on US weather were referred to as E and F. Different cities were used to build certificates C–D and E–F for each market period, so that the amount of uncertainty was not diminished by market experience. Uncertainty about the actual temperature observed was solved at the end of each market period by connecting to www.weather.com, a US-based service offering information on weather forecast and averages for a large number of cities worldwide.

Also, this experiment replicates Heath and Tversky’s pricing experiment 5 on a within-subject basis.\textsuperscript{8} Prior to the beginning of market periods 1, 5, 9, 12, preference for the judgemental bets vs. the chance bets, and certainty equivalents were elicited. Five market sessions with eight traders each were run.

In Experiment 2, in a pre-market assessment, subjects stated whether they considered themselves competent/incompetent about 70 cities (European and American). Cities about which traders considered themselves competent were then used to build certificates C and D traded in the experimental markets, whereas cities about which traders felt incompetent were used to build certificates E and F. Thus, unlike Experiment 1, knowledge judgements about the individual cities were endogenous, i.e. they were explicitly formulated by traders. This second experiment was clearly meant to allow for the possibility that competence judgements were affected not so much by the location of the town, but rather by personal experience and travel, and cultural interests. Five market sessions were run.
TABLE I

<table>
<thead>
<tr>
<th></th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUM(AB)</td>
<td>31015</td>
<td>21687</td>
<td>12923</td>
<td>19770</td>
<td>22213</td>
</tr>
<tr>
<td>(st. dev.)</td>
<td>(12226)</td>
<td>(6164)</td>
<td>(3439)</td>
<td>(5918)</td>
<td>(4571)</td>
</tr>
<tr>
<td>SUM(CD)</td>
<td>21541</td>
<td>17964</td>
<td>15515</td>
<td>15690</td>
<td>11891</td>
</tr>
<tr>
<td>(st. dev.)</td>
<td>(10276)</td>
<td>(4873)</td>
<td>(6526)</td>
<td>(3774)</td>
<td>(6746)</td>
</tr>
<tr>
<td>SUM(EF)</td>
<td>20483</td>
<td>11774</td>
<td>15314</td>
<td>18117</td>
<td>13471</td>
</tr>
<tr>
<td>(st. dev.)</td>
<td>(6408)</td>
<td>(4745)</td>
<td>(6148)</td>
<td>(9122)</td>
<td>(4561)</td>
</tr>
</tbody>
</table>

4. RESULTS

4.1. Prices

As discussed in Section 3.2, the ambiguity aversion hypothesis implies that the sum of prices for chance certificates exceeds the sum of prices for judgemental probability certificates, i.e. $\text{SUM(CD)} < \text{SUM(AB)}$ and $\text{SUM(EF)} < \text{SUM(AB)}$, whereas the competence hypothesis entails that $\text{SUM(CD)} > \text{SUM(AB)}$ and $\text{SUM(EF)} < \text{SUM(AB)}$. Table I presents the overall mean sum of prices and standard deviations per session in Experiment 1, and shows that in all sessions but S3 the sum of prices for chance certificates exceeds the sum of prices for judgemental certificates. $\text{SUM(CD)} > \text{SUM(EF)}$ only in sessions S1, S2 and S3, which suggests that E–F are not always perceived as more ambiguous than C–D. The differences in the sum of mean prices amongst the three types of assets are statistically significant by a Friedman test in two sessions only (S2: chi-square = 15.5, $p < 0.01$; S5: chi-square = 10.5, $p < 0.01$). Concerning volatility, standard deviations of the sum of mean prices over periods do not exhibit any discernible pattern.

Figure 1 S1–S5 presents the dynamics of mean prices through the experimental periods. Each figure represents a session. The no arbitrage price of 10,000 francs is also shown, as a solid black line. The figures show that in most sessions
TABLE II
Equilibrium prices in Experiment 1

<table>
<thead>
<tr>
<th>Session</th>
<th>A+B</th>
<th>C+D</th>
<th>E+F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32719.6</td>
<td>25009.0</td>
<td>28045.7</td>
</tr>
<tr>
<td>2</td>
<td>23553.6</td>
<td>21399.6</td>
<td>12534.9</td>
</tr>
<tr>
<td>3</td>
<td>14079.3</td>
<td>24530.4</td>
<td>20872.3</td>
</tr>
<tr>
<td>4</td>
<td>18481.1</td>
<td>17234.6</td>
<td>16596.2</td>
</tr>
<tr>
<td>5</td>
<td>21820.8</td>
<td>10806.1</td>
<td>13551.6</td>
</tr>
</tbody>
</table>

and periods prices exceed the no arbitrage value and there is no clear convergence towards a common value. Concerning the comparison between the prices of the three types of assets, in three sessions (S1, S2, S5) the sum of mean prices for the chance certificates (A+B) is clearly higher than that for the judgemental lotteries, whereas in S4 prices for chance bets are higher than those of the other assets only in the initial periods of the experiment. Hence, this preliminary analysis lends support to the ambiguity aversion hypothesis, whilst there is no evidence of a competence effect in prices.

In order to explore the issue of price dynamics and convergence further, stationary prices per session were estimated using a simple first-order auto-regressive equation: $P_t = \alpha + \beta P_{t-1} + \epsilon_t$, where $P_t$ and $P_{t-1}$ are mean sum of prices at time $t$ and $t-1$, respectively, and $\epsilon_t$ is white noise. Let $a$ and $b$ be OLS estimates of $\alpha$ and $\beta$. Then, the equilibrium price can be estimated by $a/(1-b)$ (Camerer, 1987). Table II shows the results of such estimation. Stationary prices further support the ambiguity aversion hypothesis, thus confirming what was revealed by the simple descriptive analysis of mean values. The sum of mean prices for chance certificates exceeds that for judgemental bets, both C+D and E+F, in all sessions except S3.

The analysis of prices in Experiment 2 provides evidence towards the presence of competence effects. Recall that in
this second experiment, traders stated in a pre-market phase whether they felt competent/incompetent to evaluate the weather of a given town. Only towns for which traders felt competent ended up as certificates of type C–D in the market.

Figure 1. (S1–S5) Mean prices in Experiment 1.
Likewise, only towns about which no trader felt competent were used to build certificates E–F. As expected, all towns about which traders felt competent were Europeans, whereas nobody felt competent about US towns. However, some of the European cities which had been used to build certificates C–D in Experiment 1, for instance Monaco/Montecarlo, were rated as low competence towns by all participants in Experiment 2, thus suggesting that the competence judgement did not rest simply on the criterion of geographical proximity.

Evidence of the effect of this self-assessed competence on prices is revealed by Tables III and IV. Mean prices reported in Table III favour the competence hypothesis in that $\text{SUM(CD)} > \text{SUM(AB)}$ and $\text{SUM(CD)} > \text{SUM(EF)}$ in four sessions, namely S1, S3, S4, S5. However, the price of chance
certificates exceeds that of low competence assets only in sessions, S3 and S5. The high competence certificates C–D turn out to be the most valued, although the difference in the distribution of mean prices for the three couples of certificates is statistically significant by a Friedman test only for sessions S1 and S5 (S1: chi-square (2) = 4.979, \( p < 0.10 \); S5: chi-square (2) = 19.5, \( p < 0.01 \)). Also, standard deviations reveal that in four sessions out of five, the price of assets C and D displays the highest inter-period variability. This variability is best visualised by Figure 2, which display mean prices per period in the five sessions of Experiment 2.

Table IV shows equilibrium prices estimated as for Experiment 1, and provides further evidence towards a stronger presence of a competence effect with respect to Experiment 1: in sessions S1, S3 and S5 certificates C-D are the most valued.

The analysis of prices discussed so far has been carried out session by session. In order to carry out a joint analysis of prices, whilst keeping the heterogeneity of sessions into account, a random effect panel model has been estimated. The dependent variable was the mean sum of prices in session \( i(i = 1, \ldots , 5) \) at time \( t(t = 1, \ldots , 12) \), whereas the independent variables were a dummy for certificates C+D, DUMMY(CD), a dummy for certificates E+F, DUMMY(EF), and exchange volumes (VOLUME). This latter variable was introduced as some experimental research has shown that overpricing is directly correlated with trade volumes (Smith et al., 1988).

Two separate equations were estimated for the two experiments. Estimates are presented in Table V. In Experiment 1, DUMMY(CD) is significant at the 95% level and bears a negative sign, implying that European certificates trade at lower prices with respect to chance certificates. In treatment 2, DUMMY(CD) is only weakly significant and carries a positive sign, pointing to the existence of a competence effect, albeit not very strong. DUMMY(EF) is negative in both equations, but it is statistically insignificant in Experiment 2. The sign for volumes differs in the two equations, and it is never statistically significant.
Figure 2. (S1–S5) Mean prices in Experiment 2.
TABLE V
Random effects panel estimation

<table>
<thead>
<tr>
<th>EXP. 1</th>
<th>Wald $\chi^2(3) = 26.75$, prob $\chi^2 = 0.00$</th>
<th>Rho = .24</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coef (SE)</td>
<td>$t$</td>
</tr>
<tr>
<td>Constant</td>
<td>18096.1(2710)</td>
<td>6.68</td>
</tr>
<tr>
<td>DUMMY CD</td>
<td>$-4626.5(1303.7)$</td>
<td>$-3.55$</td>
</tr>
<tr>
<td>DUMMY EF</td>
<td>$-5005(1339.2)$</td>
<td>$-3.74$</td>
</tr>
<tr>
<td>VOLUME</td>
<td>216.4 (115.6)</td>
<td>1.87</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EXP. 2</th>
<th>Wald $\chi^2(3) = 7.16$, prob $\chi^2 = 0.067$</th>
<th>Rho = 0.21</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coef (SE)</td>
<td>$t$</td>
</tr>
<tr>
<td>Constant</td>
<td>18220 (2418.7)</td>
<td>7.53</td>
</tr>
<tr>
<td>DUMMY CD</td>
<td>1906.7 (1152.3)</td>
<td>1.65</td>
</tr>
<tr>
<td>DUMMY EF</td>
<td>$-525(1158.2)$</td>
<td>$-0.45$</td>
</tr>
<tr>
<td>VOLUME</td>
<td>$-180(109.9)$</td>
<td>$-1.64$</td>
</tr>
</tbody>
</table>

4.2 Convergence of prices to the no arbitrage value

Stationary prices shown in Tables II and IV can be used to evaluate whether the sum of prices for complementary certificates converges to the no arbitrage value of 10,000 francs. As the tables show, equilibrium prices are in most cells below mean prices, but they are well above the no arbitrage value, except in one session out of ten, namely session S2 in Experiment 2. The persistence of overpricing implies that little learning of the equilibrium price took place in the course of the session. Although these findings are common to other experiments who share the same design, for instance Rietz (1999) and Weber et al. (2000), nevertheless, deserve some discussion, as they are at odds with other market experiments reported in the literature. A classic paper on information dissemination in markets, such as Plott and Sunder (1982)
finds that prices converge to the rational expectations equilibrium. In that experiment, information about the state of the world that occurs is asymmetrically distributed amongst players who trade a single-period asset for several periods. The relevance of informed traders in the process of price convergence is underlined by Sunder (1992) who shows that as the number of informed traders in the market diminishes the dissemination of information becomes “chancier” (Sunder, 1995, p. 455).

In markets in which information is publicly available and symmetric, price bubbles are more common. Porter and Smith (2003) argue that price bubbles are “a robust phenomenon against significant structural and environmental changes”. The path-breaking piece of experimental evidence on price bubbles, namely Smith et al. (1988), shows that in a market in which inexperienced players trade an asset living for 15 periods, bubbles are standard. However, after common group experience for two sessions, prices converged to fundamental value in the third.

Lack of experience is the most likely explanation for the results reported in this experiment. One could reason that since all subjects in the experiment were first time participants to market experiments, they would have needed more than 12 repetitions. O’Brien and Srivastava (1991) argue that understanding and exploiting arbitrage opportunities may not come naturally. Rietz (1999) shows that even with assets living one period, only the presence of a professional arbitrager who exploits every single arbitrage opportunity succeeds in driving asset prices in an experimental sessions to their fundamental value.9

Further, the persistence of overpricing may be tied to some features of the design. For instance, absence of real out-of-pocket losses for traders may have played a role. Subjects who went bankrupt actually lost only their participation fee, and this may have reduced their incentive not to buy at excess prices.
4.3. Market prices vs. certainty equivalents

Market prices for assets can be contrasted with certainty equivalents and preference statements to bet over lotteries, as stated by the subjects prior to market evaluation. In particular, before the beginning of market periods 1, 5, 9 and 12, participants in Experiment 1 were asked whether they preferred to bet either on a statement concerning the temperature of a EU or US city, and then they were asked whether they preferred to bet on the chosen statement or on the toss of a coin. Preference for and against every bet were recorded. Finally, participants gave their certainty equivalent of the complementary bets concerning the EU and the US towns. No incentive was provided and traders were informed that their answers did not affect their subsequent results in the market. This leg of the experiment mimics Heath and Tversky’s experiment 5 on a within-subject basis, and provides a straightforward comparison with values elicited in the market setting.

Table VI shows the proportion of choices on betting on own judgement (i.e. on the temperature) vs. a chance lottery. Both preferences for and against the lotteries are reported. As the table shows, betting on one’s own judgement was always the modal choice, so this analysis suggests the existence of a competence effects, similarly to what is found by Heath and Tversky. The preference judgement, however, is not reflected in market prices.

As far as certainty equivalents are concerned, Table VII displays the mean sum of certainty equivalents for complementary bets of EU and US town, respectively, averaged over periods 1, 5, 9 and 12. Again, results confirm the findings of Heath and Tversky’s experiment, in that the sum of certainty equivalents for high knowledge bets exceeds in all sessions those for low knowledge bets. Thus, certainty equivalents are in contrast with market prices, suggesting that US bets are not always perceived as more ambiguous than EU ones. Also, the mean sum of certainty equivalents is substantially lower than the sum of mean prices, albeit much more variable. Speculation may be at the root of this difference, i.e. overpricing
TABLE VI

Frequency (%) of preference to bet on own judgement vs. chance bet (average over four repetitions)

<table>
<thead>
<tr>
<th></th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Judgement</td>
<td>59.4</td>
<td>46.9</td>
<td>59.4</td>
<td>34.4</td>
<td>46.9</td>
</tr>
<tr>
<td>Chance</td>
<td>28.1</td>
<td>21.9</td>
<td>21.9</td>
<td>34.4</td>
<td>46.9</td>
</tr>
<tr>
<td>Indifference</td>
<td>12.5</td>
<td>31.3</td>
<td>18.8</td>
<td>31.3</td>
<td>6.3</td>
</tr>
<tr>
<td>Judgement&lt;sup&gt;C&lt;/sup&gt;</td>
<td>56.3</td>
<td>46.9</td>
<td>71.9</td>
<td>65.6</td>
<td>59.4</td>
</tr>
<tr>
<td>Chance&lt;sup&gt;C&lt;/sup&gt;</td>
<td>15.6</td>
<td>15.6</td>
<td>15.6</td>
<td>18.8</td>
<td>37.5</td>
</tr>
<tr>
<td>Indifference</td>
<td>28.1</td>
<td>37.5</td>
<td>12.5</td>
<td>15.6</td>
<td>3.1</td>
</tr>
</tbody>
</table>

C denotes the complementary bet.

TABLE VII

Mean and standard deviations (in parenthesis) of the sum of certainty equivalents

<table>
<thead>
<tr>
<th></th>
<th>EU</th>
<th>US</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>6421.4 (8042.0)</td>
<td>5218.9 (6600.5)</td>
</tr>
<tr>
<td>S2**</td>
<td>15940.2 (21938.4)</td>
<td>10827.7 (17548.9)</td>
</tr>
<tr>
<td>S3*</td>
<td>10940.6 (3999.2)</td>
<td>10578.4 (9156.4)</td>
</tr>
<tr>
<td>S4**</td>
<td>10426.6 (9671.8)</td>
<td>8680.9 (8063.1)</td>
</tr>
<tr>
<td>S5*</td>
<td>5261.0 (6922.2)</td>
<td>4024.9 (5237.7)</td>
</tr>
</tbody>
</table>

*Asymp. Sig. (2 tailed) < 0.01.
**Asymp. Sig. (2 tailed) < 0.1.

in the market may be driven by the hope of reselling at higher prices (Lei et al., 2001).

4.4. Exchanges and final holdings

Trade volumes reported in Table VIII point out that there was moderate trading in both experiments. Taking into consideration that traders’ initial endowment in terms of certificates was a risky position made up either by 2A, 2C, 2E or 2B, 2D, 2F, the minimum number of trades per subject to achieve a
fully hedged portfolio was six. In most sessions of Experiment 2, mean trades per periods were below 24, the minimum number of exchanges required for all traders to achieve fully hedged portfolios.

Traders, however, did move towards the certainty line. Let’s define the market’s risk-sharing efficiency as the proportion of assets that in final market allocations is made up of risk-free portfolios i.e. couples of complementary certificates. Final allocations had an average risk-sharing efficiency of 0.47 in Experiment 1 and of 0.64 in Experiment 2.¹¹

In order to check whether exchange activity depends on the type of certificates traded, Table VIII also reports the number of total trades for certificates A–B, C–D and E–F. There is neither evidence of a higher trading frequency of chance certificates over judgemental certificates, nor of a preference for assets C–D. This means that results do not support any of the two hypotheses concerning volumes. Volumes were in the majority of case not statistically different between chance-based and event-based assets. Asterisks in Table VIII signal

---

### TABLE VIII
Trade volumes

<table>
<thead>
<tr>
<th>Exp 1</th>
<th>S1</th>
<th>S2*</th>
<th>S3</th>
<th>S4</th>
<th>S5*</th>
</tr>
</thead>
<tbody>
<tr>
<td>A+B</td>
<td>73</td>
<td>142</td>
<td>81</td>
<td>92</td>
<td>87</td>
</tr>
<tr>
<td>C+D</td>
<td>84</td>
<td>89</td>
<td>91</td>
<td>98</td>
<td>61</td>
</tr>
<tr>
<td>E+F</td>
<td>67</td>
<td>69</td>
<td>90</td>
<td>89</td>
<td>65</td>
</tr>
<tr>
<td>MEAN TRADES PER PERIOD</td>
<td>18.67</td>
<td>25.00</td>
<td>21.83</td>
<td>23.25</td>
<td>17.75</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exp 2</th>
<th>S1*</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
</tr>
</thead>
<tbody>
<tr>
<td>A+B</td>
<td>63</td>
<td>73</td>
<td>73</td>
<td>97</td>
<td>118</td>
</tr>
<tr>
<td>C+D</td>
<td>81</td>
<td>59</td>
<td>70</td>
<td>88</td>
<td>130</td>
</tr>
<tr>
<td>E+F</td>
<td>58</td>
<td>69</td>
<td>63</td>
<td>88</td>
<td>133</td>
</tr>
<tr>
<td>MEAN TRADES PER PERIOD</td>
<td>16.83</td>
<td>16.75</td>
<td>17.17</td>
<td>22.75</td>
<td>31.75</td>
</tr>
</tbody>
</table>

*Distribution of trades significantly different at the 95% level by a Friedman test.
those sessions for which the distribution of trades through time differs according to the type of certificate, with a significance level of 95% (Friedman test).

5. DISCUSSION

This experiment has investigated whether natural event ambiguity affects market prices and volumes. Ambiguity generated by real events is more of interest to real-world decision making with respect to chance-based operationalisations of ambiguity, since the payoffs of most real-world production, purchase and sale decisions are characterised by the former rather than the latter.

Mean prices observed in all experimental sessions exhibit either ambiguity aversion or ambiguity seeking. More precisely, in Experiment 1, where knowledge concerning alternative bets is exogenously established by the monitor, pricing behaviour is consistent with ambiguity aversion. Certificates whose liquidating value depends on chance trade at higher prices with respect to certificates whose value depends on the temperature recorded in a given town. In Experiment 2, where the decision maker herself tells high knowledge propositions from low knowledge ones, ambiguity seeking behaviour may be explained by Heath and Tversky’s competence hypothesis. In most sessions, high competence certificates are priced more than equivalent chance and low competence certificates.

Competence and ambiguity aversion affect prices, but not market volumes: exchanges do not differ significantly amongst types of certificates.

Experiment 1 was built following Heath and Tversky’s experiment 5, in the sense that knowledge for home events was assumed to be higher than for foreign events. However, the different results between Experiments 1 and 2 and, in particular, the prevalence of ambiguity aversion in Experiment 1, points out that caution must be used in designing experiments meant to capture competence effects. Since perceived competence is most likely rooted in the subject’s personal experience,
a check of the robustness of competence effects across alternative specification of “knowledge” is required. Thus, more market tests adopting manipulation checks are needed.

The results of Experiment 2 imply that feelings of competence play a role in affecting the functioning of markets, as other papers have suggested. Behaviour influenced by “perceived competence” may explain for instance the so-called *home bias* in asset markets (Kilka and Weber, 2000). The home bias phenomenon refers to the incomplete diversification of asset portfolios, caused by the fact that investors’ portfolios tend to be made up mainly of domestic assets. Since French and Poterba (1991), it has been recognised that it is behavioural factors rather than institutional explanations which matter most in determining the home bias. More precisely, expectations about returns vary according to the nationality of investors, so that, for instance, Americans will expect higher returns from investing on the Dow–Jones index rather than on the Nikkei, whilst the opposite holds for Japanese investors.12

A key feature of this experiment was the introduction of natural event ambiguity in a double auction market. Markets are reputed as settings in which distortions with respect to the rational model of behaviour are reduced due to repetition, feedback and incentives. However, in order to be able to attribute values elicited in markets to market incentives and discipline, these latter must be truly *market-specific*, rather than consist of generic reinforcement tools such as repetition, monetary rewards and feedback from other experiment participants, which can be obtained also through other elicitation methods.

The design adopted in this experiment should have provided discipline such that price distortions due to ambiguity or to perceived competence should have been removed by arbitraging. Results show that pricing displays the same biases observed in non-market environments. Further, ambiguity reaction is reflected in mean prices in most sessions in a pronounced fashion without any evidence of convergence to a common value. This finding parallels that of Sarin and
Weber (1993)'s experiment, in which ambiguous and unambiguous assets are traded simultaneously,\(^{13}\) and has been attributed to a “comparative ignorance” effect (Fox and Tversky, 1995), whereby direct comparison between two events induces a feeling of being relatively more ignorant in one of them. However, Sarin and Weber's design excludes the possibility of arbitraging, and thus the learning process of the equilibrium price relies on the repetition of the market experience (eight market rounds were run) and on the feedback provided by market prices.

So, why does a marked reaction to ambiguity persist in this experiment? A clue is supplied by the fact that previous market research has adopted chance processes to make uncertainty operational. This suggests that uncertainty generated by natural events may give rise to persistent ambiguity effects. This hypothesis, however, awaits further tests.

It must also be acknowledged that some of the results obtained may be due to limitations of the present paper. In particular, the absence of price convergence to the no arbitrage value may be due to the fact that subjects were at their first experience with market experiments, and that they needed more in-depth information on how to arbitrage. As part of the research agenda, it is planned to address these issues by contrasting the market behaviour of experienced vs. inexperienced subjects.

ACKNOWLEDGEMENTS

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NOTES

1. Mukerji and Tallon (2003) have generalised Dow and Werlang’s results without invoking a parametric preference form.
2. Evidence on attitude towards real event uncertainty is restricted to non-market experiments (amongst others Tversky and Fox, 1995; Fox et al., 1996).
3. Francs is the fictitious currency in which trades during the experiment were denominated.
4. See also Rietz (1999) and Weber et al. (2000) for other examples of this design.
5. For certificates based on the temperature, traders were informed at the beginning of the experiment that the temperature could not be exactly equal to the historical average for that day.
6. Risk-neutral traders are indifferent between holding one type of certificate or the other, and risk seeking traders prefer to hold only one type of certificate.
7. The endowment was a zero-interest loan that had to be repaid at the end of each market period.
8. Heath and Tverky’s results are between-subject.
9. In a different strand of research with respect to ours, List (2004) shows that a violation of expected utility theory such as the endowment effect disappears in markets only when professional traders are involved.
10. Namely, the two cities that were going to be used in the subsequent market period.
11. In particular, in Experiment 1, average risk-sharing efficiency in each session was as follows: $S_1 = 0.44$, $S_2 = 0.44$, $S_3 = 0.66$, $S_4 = 0.48$, $S_5 = 0.33$. In Experiment 2: $S_1 = 0.63$, $S_2 = 0.69$, $S_3 = 0.64$, $S_4 = 0.67$, $S_5 = 0.59$.
12. Another behavioural explanation is based on the notion of over-confidence.
13. When ambiguous and unambiguous assets were traded independently, convergence of prices was observed by the authors.

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