

An Empirical Investigation of the Assumptions of Risk-Value Models

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Do subjects make decisions consistent with risk-value tradeoffs? One hundred and five undergraduate business students made risk and preference judgments about lottery pairs in a series of paper surveys. The data indicate that the subjects' responses were consistent with risk independence and other key assumptions of risk-value models for both perceived risk and preference. Support is provided for the risk-value paradigm popular in finance and psychology, and some extensions are considered.

keywords: Risk measures, risk-value models, utility theory

1. Introduction

The valuation of uncertain prospects reduces to two core considerations: 1) the probability or uncertainty regarding the possible outcomes, and 2) the value associated with those outcomes. The fields of psychology and financial economics assert that decision makers approach this difficult judgment task by making a tradeoff between the risk (uncertainty) and the value associated with a risky proposition. For example, when selecting a group of stocks for an investment, a prospective investor may wish to trade off the variance of the portfolio return (risk) against the level of the expected return (value). This intuitive concept of a mean-variance tradeoff is used as the objective function in many portfolio optimization algorithms, including Markowitz's (1959) seminal work.

Numerous scholars have developed theories of risk and preference as independent concepts, but efforts to link these two primitive concepts are less common. In von-Neumann and Morgenstern's (1947) expected utility theory, the measure of risk aversion (Pratt, 1964; Arrow, 1971) is simply based on the shape of a utility function, confounding the exact relationship between risk perception and preference. Similarly, many risk measures (e.g., Coombs and

Lehner, 1981, 1984; Luce and Weber, 1986; Keller, Sarin and Weber, 1986; Weber and Bottom, 1990) require judgments that cannot be linked directly to preference.

In this paper we describe the results of an empirical study that investigates the underlying assumptions of models providing an explicit link between risk and preference: Jia and Dyer (1996), and the related work of Sarin and Weber (1993) and Bell (1995). Jia and Dyer (1996) develop a standard measure of risk consistent with the expected utility theory, and therefore it provides a relationship between the notions of risk and preference. This risk measure can also be used as a component in a more general risk-value framework of decision making to explicitly capture risk-value tradeoff behavior (Jia, 1995; Jia and Dyer, 2001). Special cases included in this framework of preference models are exponential and linear plus exponential utility models, mean-variance and mean-semi-variance models, and disappointment models. Specifically, we report the results of several related experiments to test whether these or any other preference models based on the intuitive appeal of a risk-value tradeoff are consistent with the choice behavior of subjects.

The underlying assumptions of risk-value theory fall into three general categories. First, risk is presumed to be the converse of preference for lotteries with zero expectation. This establishes a fundamental relationship between risk and preference. Second, the axioms of utility theory are assumed to hold for all lotteries with zero expected value. While there are many examples of the descriptive failure of utility theory in general, risk-value theory only requires consistency with von-Neumann and Morgenstern's axioms for this subset of risky propositions. Finally, the risk and preference rankings of any pair of lotteries with the same expected value are presumed to be invariant to adding any constant to all outcomes of the pair. We refer to these two underlying assumptions as risk independence for risk perception and for preference,

respectively. All three of these categories of assumptions must be satisfied in order to justify the use of any of the preference models that are special cases of the risk-value framework.

The remainder of this paper is organized as follows. Section 2 provides a brief review of risk-value theory, focusing on the aspects of the theory that will be tested. Section 3 describes the experimental stimuli that were chosen as well as the setting and subjects who participated in the experiments. Section 4 presents our findings using an analysis that explicitly models the errors inherent in human judgments. Section 5 provides an extension of the risk independence assumptions that explains a pattern of choices common to some of the subjects in the experiments. Section 6 concludes this experimental study and discusses relevant issues.

2. Risk-value Theory

Let X be a random variable representing a lottery with mean \bar{X} . Then the normalized lottery $X' = X - \bar{X}$ has zero expected value and represents the “pure” risk associated with the lottery X . We refer to this dispersion about the mean as the standard risk. Since any lottery can be transformed in this way, the mean and standard risk are featured in a two-attribute structure (\bar{X}, X') for evaluating a lottery in risk-value theory. Based on the axioms of multi-attribute utility theory and a risk independence condition, a risk-value model, $f(\bar{X}, X')$, can be expressed in the following form (Jia, 1995; Jia and Dyer, 2001):

$$f(\bar{X}, X') = V(\bar{X}) - \phi(\bar{X})[R(X') - R(0)] \quad (1)$$

where $V(\bar{X})$ is an increasing function of the mean \bar{X} and can be interpreted as the value measure, $\phi(\bar{X}) > 0$ is a tradeoff factor that may depend on the mean \bar{X} , $R(X') = -E[u(X')] = -E[u(X - \bar{X})]$ is a standard measure of risk (Jia and Dyer, 1996), the

symbol E represents the expectation operator, and $R(0) = -u(0)$ is a constant, where $u(\cdot)$ is the von Neumann and Morgenstern utility function defined on the set of lotteries with zero expected values.

Model (1) is consistent with the expected utility model when $V(\cdot) = u(\cdot)$ and $\phi(\bar{X}) = u''(\bar{X})/u''(0)$. Specifically, the quadratic, exponential and linear plus exponential utility functions can be represented in the form of a risk-value model (1). Further, the risk-value preference structure includes many previously developed decision models as special cases. The disappointment models (Bell 1985; Loomes and Sugden, 1986) subsume many of the models used in financial optimization and are easily represented via (1) (Jia, Dyer and Butler, 2001).

The term $\phi(\bar{X})[R(X') - R(0)]$ in the risk-value model (1) measures the impact of risk on preference. It also provides a suitable measure of perceived risk if $\phi(\bar{X})$ is a decreasing function of the mean, \bar{X} (Jia, Dyer and Butler, 1999). In general, the measure of perceived risk is based on the converse interpretation of the axioms of risk-value preference theory. Therefore, a negative linear transformation of the risk-value model (1) provides a measure of perceived risk. When the tradeoff factor is a constant, $\phi(\bar{X}) = k$, perceived risk is expressed as $-V(\bar{X}) + kR(X')$ ¹. Special cases of this measure of perceived risk include Pollatsek and Tversky's (1970) mean-variance risk model (when $V(\bar{X})$ is linear and $R(\bar{X})$ is equal to variance) and Rotar and Sholomitsky's (1994) moments risk model (when $R(\bar{X})$ is a linear combination of higher order moments).

These risk-value models and measures of perceived risk rest on four key assumptions that are investigated in this empirical study. The first two assumptions relate to the critical role

¹ We drop the constant $kR(0)$ based on the negative linear transformation property.

played by the von Neumann-Morgenstern utility function defined on lotteries with zero mean, since its converse is the basis for the standard measure of risk.

Let P^0 be the set of normalized lotteries with zero-expected values, \succ a strict preference relation and \succ_R a strict risk relation meaning “more risky”.²

Assumption 1: Risk and preference relation for lotteries with $E[X]=0$. For $X', Y' \in P^0$, $X' \succ Y'$ if and only if $Y' \succ_R X'$.

This assumption establishes a critical relationship between preference and risk in risk-value theory, i.e., preference ordering and risk ordering are conversely consistent for lotteries with zero expected value. Intuitively, since both $X', Y' \in P^0$ have mean zero, the choice between them should be based solely on their pure risk. For a risk-averse individual, a riskier lottery would be less preferable, while a risk seeker would prefer a riskier prospect.

In a related study, Weber and Bottom (1990) asked subjects to compare 28 pairs of monetary lotteries with equal expected values, and to indicate which lottery was more risky and also which lottery they would choose. 76% of their subjects selected lotteries that they also judged to be less risky or equally as risky, which would be consistent with the spirit of Assumption 1. However, their lotteries did not have zero means, so we elected to explore similar responses for this domain.

Assumption 2: Substitution for normalized lotteries with $E[X]=0$. For $X', Y', Z' \in P^0$, if $X' \succ Y'$ then $\alpha X' + (1 - \alpha) Z' \succ \alpha Y' + (1 - \alpha) Z'$ for any $\alpha \in [0, 1]$.

² We use “ \succ ” and “ \succ_R ” for both one-attribute relation and two-attribute relation in this paper.

This is a key assumption in the expected utility theory, and several empirical tests have shown it to be violated (e.g., see the discussion in Camerer (1995)). The difference here is that this condition is restricted to the subset of normalized lotteries with zero-mean. In general, expected utility theory has been questioned as a descriptive theory, but to our knowledge, there has never been a test of lotteries with zero-mean only. For example, behavior consistent with the Allais paradox can be ignored because it requires a group of lotteries with different and non-zero means. Assumptions 1 and 2 together allow us to simply use the converse of expected utility for the standard measure of risk, i.e., $R(X') = -E[u(X')] = -E[u(X - \bar{X})]$.

Perhaps the most critical assumptions of risk-value theory are two notions of risk independence, one for risk judgments and the other for preference judgments.

Assumption 3: Risk independence for perceived risk. For $X', Y' \in \mathcal{P}^0$, if there exists a $w_0 \in \mathcal{R}$ for which $(w_0, X') \succ_R (w_0, Y')$, then $(w, X') \succ_R (w, Y')$ for all $w \in \mathcal{R}$.

Assumption 3 states that for a pair of lotteries with a common mean, the risk ranking of the two lotteries will not change when the common mean changes. In other words, the relative riskiness of two lotteries with the same mean is solely determined by the pure risk, X' , of the lotteries.

This assumption is also similar in spirit to Pollatsek and Tversky's (1970) additive independence condition for their mean-variance risk model, but Assumption 3 is weaker since it is restricted to lotteries with the same means and employs a common constant instead of a common lottery. In general, this risk independence condition does not lead to a simple additive model of perceived risk, though it is a special case.

Coombs (1975) provided some empirical evidence supporting Assumption 3, but here we investigate it directly and comprehensively. In contrast, Weber and Milliman (1997) report some

switching in the risk rankings of high versus low variance lottery pairs when they are transformed from the loss domain to the gain domain. However, they did not restrict their experiments to lotteries with common means.

Assumption 4: Risk independence for preference. For $X', Y' \in P^0$, if there exists a $w_0 \in Re$ for which $(w_0, X') \succ (w_0, Y')$, then $(w, X') \succ (w, Y')$ for all $w \in Re$.

This condition is identical to risk independence for risk judgments, but here is applied to preference judgments or choice. Assumption 4 requires that if two lotteries have the same expected value and one is preferred to the other, then transforming the lotteries by adding the same constant to all outcomes will not reverse the preference ordering. This condition is related to the concept of utility independence in multi-attribute utility theory (Keeney and Raiffa, 1976), and leads to the separable form of the risk and value model (1).

In an early experiment, Edwards (1954) found that choice patterns among lotteries at different levels of common means were substantially the same, i.e., independent of the mean. Though Edwards focused on a different issue, his study provides supporting evidence for the assumption of risk independence.

However, Payne, Laughhunn, and Crum (1980, 1981) obtained results that were inconsistent with the risk independence for preference judgments using pairs of three-outcome lotteries with both positive and negative outcomes. When the addition of a constant moved all the outcomes of one lottery either entirely above or below the assumed reference point of \$0, but was not sufficient to move all the outcomes of the other lottery above or below \$0, then they observed many subjects shifting their preferences. Weber and Milliman (1997) also observed

some switches in preferences as lottery pairs were shifted from the loss to the gains domain, but again their lotteries did not have common means.

We will conduct a direct test of Assumptions 3 and 4 using lottery pairs with all positive outcomes, all negative outcomes, or with zero means. The relationships between our findings and those of Payne, Laughhunn, and Crum and of Weber and Milliman will then be discussed.

3. Methodology

Students from the University of Texas at Austin (UT) and The Chinese University of Hong Kong (CUHK) were recruited to participate in the study as subjects. The 54 UT students were all taking an undergraduate introductory statistics course that covered histograms, probability and expected value. Similar recruiting efforts at CUHK yielded 51 volunteers for a total of 105 subjects. The subsequent analysis of the data indicated that there were no qualitative differences between responses of the subjects from these two groups, so they are combined in the discussion of the results of this study.

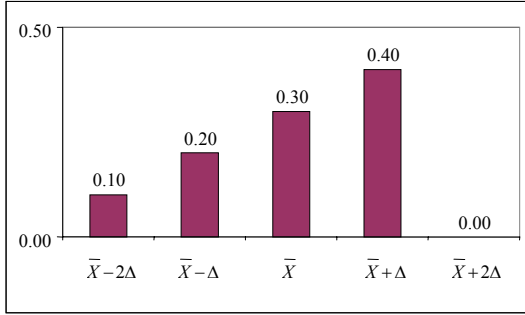
The participants were brought to a small conference room in groups of two to eight. Subjects were shown example stimuli and a brief discussion of the general concepts of risk and value followed.

Subjects were asked to complete eight separate ten-page paper surveys during an experimental session. The first page was a title page with a space for the subject to place an identifying mark, not a proper name, so that we could identify each subject's surveys without sacrificing anonymity. The second page of each survey contained instructions (the appendix contains an example). Each page thereafter consisted of the comparison of one or more pairs of lotteries. Subjects were randomly assigned to begin with either risk or preference booklets.

Different colors for each booklet were used to emphasize that while the stimuli appeared similar visually, each booklet was a distinct task. After completion of the first four booklets a short break was taken to relieve cognitive stress and to prevent drastically different completion times. On average the experimental sessions lasted about 90 minutes, and participants were paid \$20 US, or the approximate amount in \$HK, for their time.

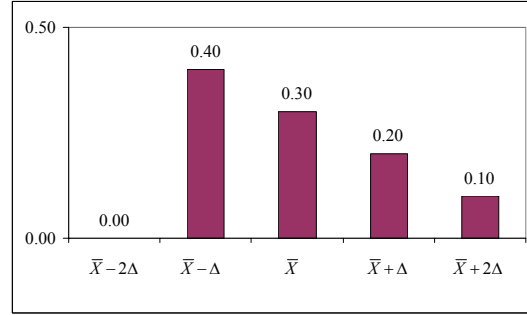
The distribution of each lottery used in the study was presented in the form of a column chart as displayed in Figure 1. There were five basic “shapes” of these distributions. The lotteries are plotted against a generic scale in Figure 1 because it is necessary to shift the means of the lotteries to test for risk independence for both risk and preference judgments. We chose $\Delta = \$500$ and the standard deviation of each lottery, $\sigma_{\Delta=500}$, is displayed for this value. Also note that immediately below each graph is a single character, s , that approximates the shape of the distribution. Because Δ is fixed for the entire experiment, we will use (\bar{X}, S) to specify a particular lottery with mean \bar{X} and shape $S = \{I, \backslash, -, ^, \vee\}$. As an example, $(1000, -)$ would represent a uniform lottery with $\bar{X} = 1000$, $\sigma = 707$, minimum outcome of \$0 ($\bar{X} - 2\Delta$) and maximum outcome of \$2000 ($\bar{X} + 2\Delta$) as depicted in the center of Figure 1.

We chose to use representations of discrete probability distributions for this study rather than continuous ones because we believed they would be easier for subjects to interpret, and they are typically used in other studies of choice. The rationale for the use of distributions that typically included five outcomes was based on the assumption that subjects would react to such lotteries in a more holistic fashion, rather than relying on simple heuristics that may easily come into play when considering two-outcome or three-outcome lotteries (e.g., select the lottery with the highest probability of the larger outcome).



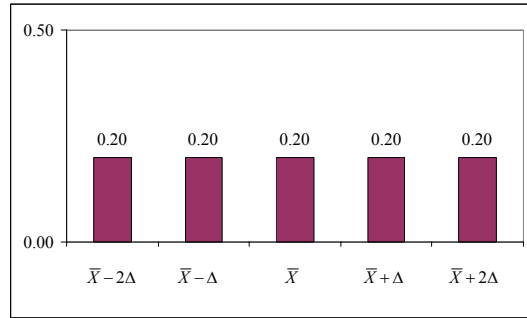
$$s = /$$

$$\sigma_{\Delta=500} = 500$$



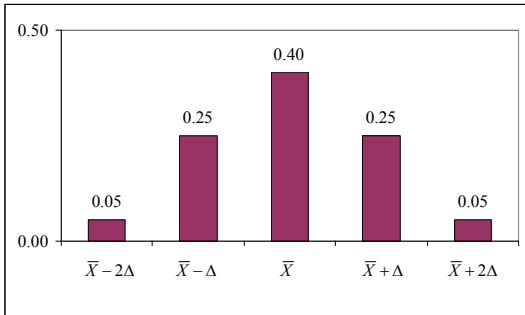
$$s = \backslash$$

$$\sigma_{\Delta=500} = 500$$



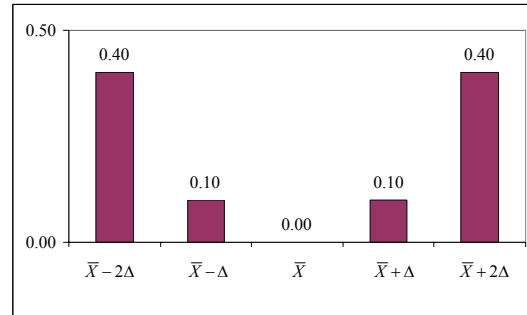
$$s = -$$

$$\sigma_{\Delta=500} = 707$$



$$s = \wedge$$

$$\sigma_{\Delta=500} = 474$$



$$s = \vee$$

$$\sigma_{\Delta=500} = 922$$

Figure 1: The Five Base Stimuli Distributions

The tests of Assumptions 1 and 2 require a set of lotteries with $\bar{X} = 0$. We chose a direct test of the assertion that preference is the converse of risk for this class of lotteries. An example is shown in Figure 2 which asks subjects for both a risk and a preference judgment for the

comparison between $(0, \lambda)$ and $(0, l)$. Risk-value theory requires that subjects respond A1 and A2 or A2 and A1.

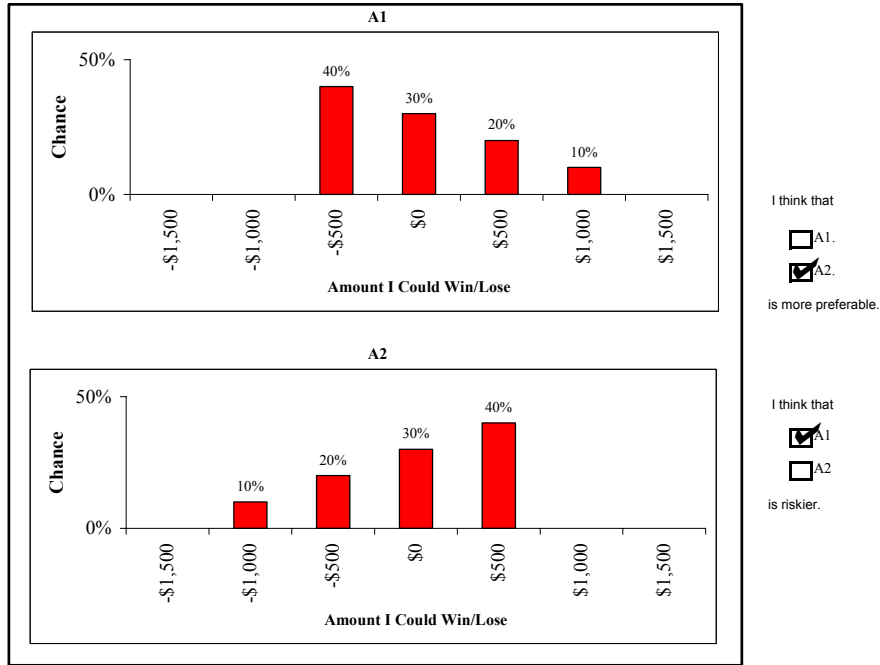


Figure 2: Example of Preference = - Risk Stimuli

Testing the substitution axiom for lotteries with $\bar{X} = 0$ requires a convolution of the base case stimuli with a common prospect; we chose a 50/50 chance to play the base lottery or to receive \$0 as the common component. An example of this transformation is provided in Figure 3 for $(0, \lambda)$. Subjects were asked to make a choice between two stimuli, say $(0, l)$ vs. $(0, V)$, and the transformations of the same pair, $((0, l), 0.5, 0)$ vs. $((0, V), 0.5, 0)$. The substitution axiom requires that a subject who prefers a particular lottery in a non-transformed pair will also prefer the transformation of the same lottery.

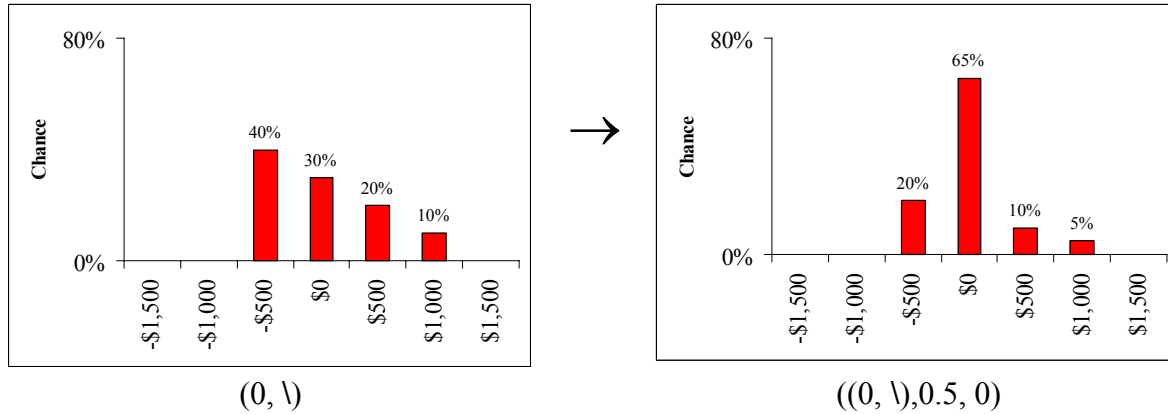


Figure 3: A convolved transformation of lottery $(0, \backslash)$

To provide a direct test of risk independence conditions for risk and preference judgments, the subjects were asked for responses to two lottery comparisons per page in the survey: a comparison between X and Y and a comparison between a transformed pair, say $X + w$ and $Y + w$. Figure 4 provides an example of a risk judgment where $A1:(1500, /)$ is compared to $B1:(1500, \backslash)$ and $A2:(2000, /)$ is compared to $B2:(2000, \backslash)$. Note that the outcomes of the lottery $A2$ equal the outcomes of the lottery $A1$ plus 500, and the outcomes of the lottery $B2$ equal the outcomes of the lottery $B1$ plus 500. The subjects were asked to tick the appropriate box for each comparison to indicate which of each pair was the more risky. Consistency with risk independence requires a subject to respond $A1$ and $A2$ or $B1$ and $B2$. Analogous stimuli were used to test risk independence for preference judgments, with the obvious labeling changes.

We restricted the outcomes in Figure 4 to be strictly positive. For symmetry we used an additional set of lotteries with $\bar{X} = -2000$ and $\bar{X} = -1500$ to test risk independence in the strictly negative domain. To assess cross-domain effects, subjects were also asked to compare $(-2000, S)$ vs. $(2000, S)$ for all pair-wise combinations of S , again making both risk and preference judgments.

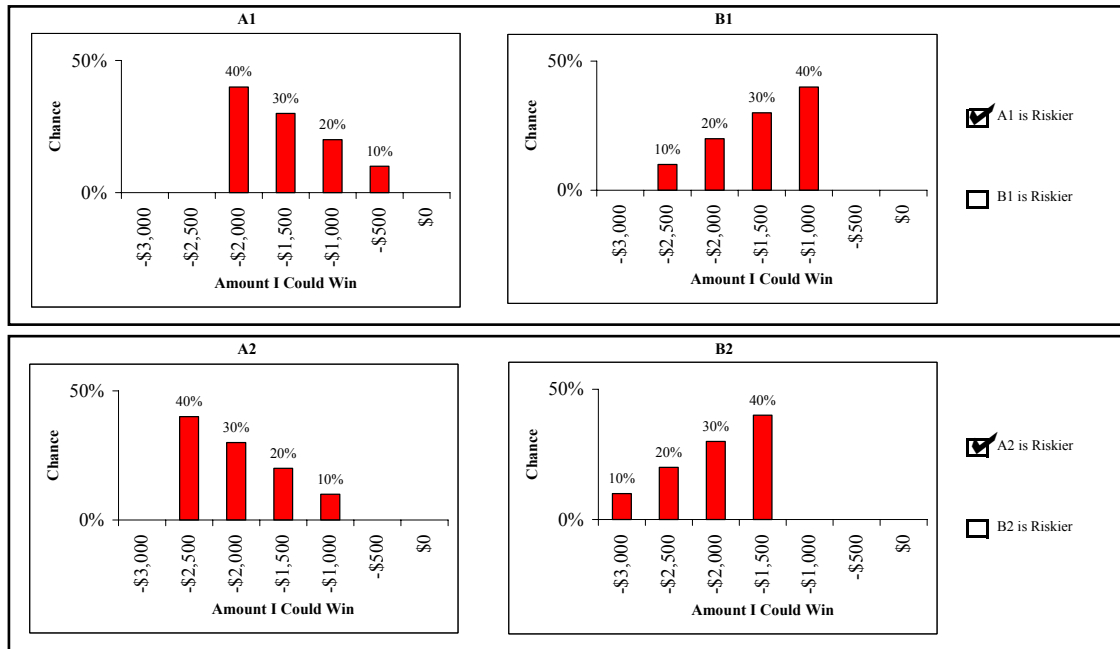


Figure 4: Example Stimuli for Risk Independence for Risk Judgments

The eight surveys completed by each subject are summarized in Figure 5. Both the page layout and the page on which a particular lottery pair appeared were randomized across booklets. This required data standardization. For example in Figures 2 and 4, the subject has indicated that \ is riskier than / in all three comparisons, but the data would be recorded as B, A1, and A2. To facilitate a quick determination of consistency with the theory we standardized all comparisons of these two lotteries so that a choice of / was recorded as an A and a choice of \ was recorded as a B. Thus the data in Figures 2 and 4 were transformed to BBB. This data triplet was extended to include choices between / and \ for $\bar{X} = -1500$ and $\bar{X} = -2000$. A subject was consistent with risk independence if her responses were AAAAA or BBBBB, where responses are listed in increasing order of the lottery means used in the comparisons from left to right. This data cleansing was repeated for all pair-wise combinations of S .

Properties of Preferences on P^0		
<i>Preference is Converse of Risk</i>	$(0, s_i)$ vs. $(0, s_j)$, <i>preference judgment</i> $(0, s_i)$ vs. $(0, s_j)$, <i>risk judgment</i> for all $s_i, s_j \in S, i \neq j$	
<i>Substitution Axiom</i>	$(0, s_i)$ vs. $(0, s_j)$ $((0, s_i), 0.5, 0)$ vs. $((0, s_j), 0.5, 0)$ for all $s_i, s_j \in S, i \neq j$	
Tests of Risk Independence		
	<i>Risk Judgments</i>	<i>Preference Judgments</i>
<i>Negative Domain</i>	$(-1500, s_i)$ vs. $(-1500, s_j)$ $(-2000, s_i)$ vs. $(-2000, s_j)$ for all $s_i, s_j \in S, i \neq j$	$(-1500, s_i)$ vs. $(-1500, s_j)$ $(-2000, s_i)$ vs. $(-2000, s_j)$ for all $s_i, s_j \in S, i \neq j$
<i>Positive Domain</i>	$(1500, s_i)$ vs. $(1500, s_j)$ $(2000, s_i)$ vs. $(2000, s_j)$ for all $s_i, s_j \in S, i \neq j$	$(1500, s_i)$ vs. $(1500, s_j)$ $(2000, s_i)$ vs. $(2000, s_j)$ for all $s_i, s_j \in S, i \neq j$
<i>Mixed Domain</i>	$(2000, s_i)$ vs. $(2000, s_j)$ $(-2000, s_i)$ vs. $(-2000, s_j)$ for all $s_i, s_j \in S, i \neq j$	$(2000, s_i)$ vs. $(2000, s_j)$ $(-2000, s_i)$ vs. $(-2000, s_j)$ for all $s_i, s_j \in S, i \neq j$

Figure 5: Summary of Experimental Design and Surveys

4. Results

A simple count of the numbers of subject choices consistent with the four key assumptions of risk-value theory provides a preliminary view of the results of the experiments summarized in Figure 5. For lotteries with expected values equal to zero, 71 percent of the subjects' judgments were consistent with risk being the converse of preference (Assumption 1), and 51 percent of the subjects were consistent with this assumption on 8 or more judgments out of 10. The results of the test of the substitution axiom are also supportive of Assumption 2: 76 percent of the judgments were consistent with the substitution axiom and 56 percent of the subjects were consistent on 8 or more judgments out of 10.

The subjects' judgments are also consistent with the assumptions of risk independence based on the comparisons of lottery pairs (Assumptions 3 and 4). For risk judgments, 91 percent and 90 percent of these judgments were consistent with risk independence in the positive and

negative domains, respectively. Similarly, in the preference tasks, the average percentage of judgments consistent with risk independence was 89 percent in both the positive domain and negative domain. However, in the mixed domain situation, the average percentage of subject responses consistent with risk independence dropped to 75 percent in risk judgments and to 59 percent in preference judgments. Thus, it is clear that the assumptions of risk independence are strongly supported when each domain is considered independently, but the results show some evidence of domain effects, especially in preference judgments. We will return to this issue in Section 5.

This summary of the results of the experiments regarding the risk independence assumptions was based on comparisons of lotteries with means of \$1500 and \$2000, and independently on comparisons of lotteries with means of -\$1500 and -\$2000. If a subject is perfectly consistent with risk independence, then her choices regarding a pair of lotteries should be the same when the common mean of the lottery pair is set at any of the five levels used in the experiments: \$2,000, \$1,500, \$0, -\$1,500, and -\$2,000. However, subjects may make errors in their responses that appear to be inconsistent with the risk independence assumptions across the three distinct domains. The fact that the stimuli have the same means, and some of them have the same or very similar variances, makes the choice tasks more difficult, and therefore more prone to response errors. In order to perform an overall test for risk independence conditions, we developed some error models that can be used as benchmarks for the results.

4.1 Error Models

The error models are based on the notion that subjects would be perfectly consistent with the risk-value model assumptions were it not for the response error inherent in their judgments. Were this true, the probability of observing the judgments of a subject for a lottery pair perfectly

consistent with the test of the assumption that preference is the converse of risk, or with the test of the substitution axiom would be $(1-\varepsilon)^2 + \varepsilon^2$ where ε is the response error. For example, in the substitution task a subject would appear to be consistent if she made two error-free judgments (e.g. AA if she prefers A) or two inaccurate judgments (e.g. BB if she prefers A).

Analogous logic can be applied to the test of the risk independence assumptions for either risk or preference judgments. The probability of observing the judgments of a subject for a lottery pair perfectly consistent with risk independence for all three domains, AAAAA or BBBBB, would be $(1-\varepsilon)^5 + \varepsilon^5$, since these tests require five judgments regarding the same lottery pair with five different means.

As noted above, we anticipated that the stimuli were likely to be viewed as very similar by the subjects. For example, a decision maker whose preferences are consistent with an exponential utility function with a risk tolerance of \$250 would find certainty equivalents of approximately \$1103 and \$992 for $(\$1500, /)$ and $(\$1500, ^)$, respectively. Is this \$11 difference in certainty equivalents going to be “significant”? It is likely that the similarity of the stimuli made it difficult for the subjects to make comparisons between lottery pairs. If the certainty equivalents were identical, or at least perceived to be, then subjects’ choices would appear to be random judgments.

Therefore, the first comparison was made with regard to the assumption that subjects simply made random choices between pairs of lotteries, which would imply the response error $\varepsilon = 0.5$. For the test of the assumption that preference is the converse of risk for lotteries with zero mean, and the test of the substitution axiom for lotteries with zero mean, random guessing would result in seemingly consistent judgments for two of the four possible patterns, or 50

percent of the time. For example, in the substitution task responses of AA or BB would appear to be consistent, while responses of AB or BA would appear to be inconsistent.

However, consistency with risk independence is determined based on 5 judgments of preference or riskiness for each lottery pair. Of the $2^5 = 32$ unique responses that are possible, only two, AAAAA and BBBBB, are consistent with risk-value theory for any pair of lotteries. Therefore, a subject choosing at random among the pairs would be consistent with risk-value theory in only 2 out of 32 attempts, which would occur with probability $0.0625 = (1-0.5)^5 + (0.5)^5$. We used two other methods to estimate the response error ε , and these are the basis for the second and third benchmarks. Recall (see Figure 5) that each subject made preference choices and risk comparisons between lotteries with $\bar{X} = \$2000$ twice: once in the *Positive Domain* and once in the *Mixed Domain*. We expected subjects to be consistent when responding to the same lottery comparisons in these two cases, were it not for the response errors in their judgments. Similarly, subjects made judgments about lotteries with $\bar{X} = -2000$ twice for both risk and preference settings, and about lotteries with $\bar{X} = 0$ twice for preference only³. We were able to use these repeated choices to estimate the subjects' response error, ε , by summing over all subjects and over all lottery pairs. The third benchmark featured $\varepsilon \in [0.15, 0.25]$, which is consistent with observed “natural” error rates when making comparisons between two items (Harless and Camerer, 1994, p. 1263).

4.2 Tests of Risk and Preference Relations for Zero Mean Lotteries

The first two analyses investigate properties of the set of normalized lotteries with $E[X] = 0$. Risk-value theory hinges on the link between risk and preference, and this link is provided by the assumption that, for these normalized lotteries only, preference is the converse of risk. The

³ A choice in the substitution test can be compared to the preference = converse of risk preference judgment.

statistical analysis strongly supports this assertion, as is evident in Table 3. The row labeled *Actual* summarizes the subjects' data. The rows labeled *Random*, *Observed*, and *Reported* correspond to the three benchmark approaches based on the error model. *Random* shows the data that would be observed if subjects made choices by flipping a coin ($\epsilon=0.5$); *Observed* shows the data that would be observed if the subjects' responses were consistent with an ϵ of 0.6091 for risk judgments, which translates to a $P(\text{Success})$ of $(1-.6091)^2 + .6091^2 = 0.5238$; *Reported* uses the endpoints and midpoint of the reported error range from Harless and Camerer (1994), setting ϵ to 0.15, 0.20, and 0.25, and leading to $P(\text{Success})$ s of 0.7450, 0.6800, and 0.6250, respectively.

Subjects indicated they preferred the lottery they viewed as less risky an average of 7.143 times based on 10 comparisons; compared with the *Random* choice benchmark, the $p\text{-value} = 5.8 \times e^{-7}$. This observed level of conformity with Assumption 1 is consistent with an error rate per response ϵ of approximately 0.0651. This low response error is outside of the range of errors commonly reported in other studies.

		Pr(Success)	Mean	Median	H ₀ : p = 0.7143 H ₀ : p > 0.7143	
Actual		0.7143	7.14	8		
Error Rate	ϵ	$(1-\epsilon)^2 + \epsilon^2$			z	$p\text{-value}$
<i>Random</i>	0.5000	0.5000	5.00	5	4.86	5.8E-07
<i>Observed</i>	0.6091	0.5238	5.24	5	4.32	7.8E-06
<i>Reported</i>	0.1500	0.7450	7.45	8	-0.70	0.7569
<i>Reported</i>	0.2000	0.6800	6.80	7	0.78	0.2183
<i>Reported</i>	0.2500	0.6250	6.25	6	2.03	0.0214

Table 1: Statistical Tests of Preference = Converse of Risk

Risk-value theory also requires the assumption that preference is captured by expected utility theory for lotteries with zero mean only. As discussed previously, when only lotteries with zero means are considered, an empirical test of the substitution axiom should provide the best evidence regarding whether actual choice behavior is consistent with this assumption. As illustrated in Table 2, this assumption also receives strong support from the subjects' judgments, e.g. for the comparison with *Random* choice, $p = 1.5 \times e^{-10}$. The subjects' high level of consistency with Assumption 2, 7.619 consistent choices out of 10 on average, corresponds to a ϵ of only 0.0528, indicating subjects found these comparisons to be relatively easy.

		Pr(Success)	Mean	Median	H ₀ : p = 0.7619 H ₀ : p > 0.7619	
Actual		0.7619	7.62	8		
Error Rate	ϵ	$(1-\epsilon)^2 + \epsilon^2$			z	p -value
<i>Random</i>	0.5000	0.5000	5.00	5	6.30	1.5E-10
<i>Observed</i>	0.6091	0.5238	5.24	5	5.73	5.1E-09
<i>Reported</i>	0.1500	0.7450	7.45	8	0.41	0.3422
<i>Reported</i>	0.2000	0.6800	6.80	7	1.97	0.0244
<i>Reported</i>	0.2500	0.6250	6.25	6	3.29	0.0005

Table 2: Statistical Tests of Substitution Axiom

One important note, the *Observed* response error of the subjects for Tables 1 and 2 was quite high: 0.6091. This is particularly curious because subjects were strongly consistent with Assumptions 1 and 2. One possible reason for the high observed-error rate is that it is based on a comparison between different stimuli displays. Specifically, the number of preference comparisons in a form consistent with Figure 2 that were identical to preference judgments for

stimuli presented in the form of Figure 3 were counted. Our conjecture is that these display changes invoked different mental rules for determining preference.

4.3 Risk Independence for Risk Judgments

It is useful to view each of the subjects as one of 105 binomial experiments with ten trials and a probability of success of $(1-\varepsilon)^5 + \varepsilon^5$ when assess the consistency of their responses with the two assumptions of risk independence. For example, if $\varepsilon = 0.5$, we could treat 0.0625 as $P(\text{Success})$ in each of 105 binomial experiments related to the risk or preference independence assumption. In the discussions of the experiments that follow, additional columns are presented to illustrate the skew of the distribution of consistent judgments.

Table 3 presents the results for the test of risk independence for risk judgments. Again, the row labeled *Actual* summarizes the subjects' data. For this row, the columns labeled *Number of Consistent Judgments* show the breakdown of the 105 participants with respect to how many of their 10 pair-wise risk judgments were consistent with the risk independence assumption. For example, exactly 5 of the 105 subjects' risk judgments were unaffected by adding a constant to all outcomes of the paired lotteries in 8 of the 10 lottery comparisons. For the rows labeled *Observed* and *Reported*, the *Number of Consistent Judgments* columns were generated based on 105 binomial experiments with the corresponding $P(\text{Success})$. For example, if subjects were making choices with $\varepsilon = 0.2000$ as in the second *Reported* row, one would expect to see $105 \times \binom{10}{3} (0.3280)^3 (1-0.3280)^7 = 27.5$ subjects who were consistent on 3 out of 10 comparisons.

The subjects were consistent with the risk independence assumption for risk judgments an average of 4.46 out of 10 of the lottery comparisons, a proportion of 0.4457. As shown in Table 3, the distribution of observed consistency is skewed to the right of the benchmark data

	Pr(Success)	Mean	Median	Number of Consistent Judgments												
				0	1	2	3	4	5	6	7	8	9	10		
Actual	0.4457	4.46	5	3.0	4.0	15.0	11.0	19.0	19.0	19.0	7.0	5.0	3.0	0.0	H ₀ : p = 0.4457	
															H ₀ : p > 0.4457	
Error Rate	ε	$(1-\varepsilon)^5 + \varepsilon^5$													z	p -value
Random	0.5000	0.0625	0.63	0	55.1	36.7	11.0	2.0	0.2	0.0	0.0	0.0	0.0	0.0	7.90	0.0E+00
Observed	0.2228	0.2842	2.84	3	3.7	14.7	26.3	27.8	19.3	9.2	3.0	0.7	0.1	0.0	3.33	0.0004
Reported	0.1500	0.4438	4.44	4	0.3	2.4	8.5	18.1	25.3	24.2	16.1	7.4	2.2	0.4	0.04	0.4842
Reported	0.2000	0.3280	3.28	3	2.0	9.6	21.1	27.5	23.5	13.8	5.6	1.6	0.3	0.0	2.43	0.0076
Reported	0.2500	0.2383	2.38	2	6.9	21.6	30.4	25.4	13.9	5.2	1.4	0.2	0.0	0.0	4.28	9.5E-06

Table 3: Subjects Consistency with Risk Independence for Risk Judgments Aggregated Across Lottery Comparisons

except for the *Reported* $\varepsilon = 0.15$ row. Table 3 also shows the results of the statistical tests of these proportions that support this observation. The interpretation is that subjects were significantly more consistent with the risk independence assumption for risk judgments than subjects choosing at random, $\varepsilon = 0.5$, but were indistinguishable from subjects with response errors of 0.15. Put another way, the probability of successfully identifying a pattern of AAAAA or BBBBB equal to 0.4457 is consistent with a response error of approximately 0.1492 for each risk comparison. This is certainly consistent with reported subject errors in other experiments in the literature. This result indicates that subjects made comparisons consistent with risk independence for risk judgments, after the allowance for a reasonable response error.

4.3 Risk Independence for Preference Judgments

A similar data aggregation and analysis was performed for the risk independence experiment for preference judgments. The data presented in Table 4 also provide support for the assertion that subjects' preference rankings of lottery pairs were unaffected by adding a constant to all outcomes. However, the consistency of these rankings with the risk independence condition for preferences is not as strong as for the case of risk judgments. The subjects' preference rankings were consistent with risk independence for 3.3 out of 10 comparisons on average, as compared to 4.46 out of 10 for risk judgments. This lower consistency is still

significantly better than a random choice strategy, and is equivalent to an error rate per response of approximately 0.1985. Again, this is within the range of error rates reported for previous experiments, suggesting that the subjects made errors at a reasonable rate. Therefore, these results do provide support for risk independence for preference judgments.

	Pr(Success)	Mean	Median	Number of Consistent Judgments											z	p-value
				0	1	2	3	4	5	6	7	8	9	10		
Actual	0.3305	3.30	3	3.0	11.0	24.0	24.0	18.0	11.0	9.0	5.0	0.0	0.0	0.0		
Error Rate	ϵ	$(1-\epsilon)^5 + \epsilon^5$														
Random	0.5000	0.0625	0.63	0	55.1	36.7	11.0	2.0	0.2	0.0	0.0	0.0	0.0	0.0	5.84	2.6E-09
Observed	0.2228	0.2842	2.84	3	3.7	14.7	26.3	27.8	19.3	9.2	3.0	0.7	0.1	0.0	1.01	0.1566
Reported	0.1500	0.4438	4.44	4	0.3	2.4	8.5	18.1	25.3	24.2	16.1	7.4	2.2	0.4	-2.47	0.9932
Reported	0.2000	0.3280	3.28	3	2.0	9.6	21.1	27.5	23.5	13.8	5.6	1.6	0.3	0.0	0.05	0.4783
Reported	0.2500	0.2383	2.38	2	6.9	21.6	30.4	25.4	13.9	5.2	1.4	0.2	0.0	0.0	2.01	0.0223

Table 4: Subjects Consistency with Risk Independence for Preference Judgments Aggregated Across Lottery Comparisons

5. Generalized Risk Independence

In general, the statistical analyses in the previous section suggest strong support for the assumptions of risk-value theory. However, systematic patterns in the data do appear that are not consistent with the “strict” interpretation of risk independence. Specifically, there is evidence that consistency *within* the gain and loss domains is strong, but that a significant number of subjects are not consistent *across* domains. The contingency tables in Figure 5 provide results in both the positive domain and the negative domain for risk judgments and preference judgments.

As discussed in the previous section, perfect consistency with risk independence would require all the judgments to be in the A_1A_2 and B_1B_2 cells both within and across domains. For example, a subject who responded A_1A_2 for $E[X] = -2000$ vs. $E[X] = -1500$ and B_1B_2 for $E[X] = 1500$ vs. $E[X] = 2000$ is consistent with a risk independence assumption within each domain, but

inconsistent when the responses are aggregated. Cells that involve inconsistent – A_1B_2 or B_1A_2 – judgments can be ignored because the theory does not make a prediction in a particular direction when response error is incorporated.

Risk Judgments					Preference Judgments								
Gains ($E[X] > 0$)					Gains ($E[X] > 0$)								
					<i>AA</i>	<i>AB</i>	<i>BA</i>	<i>BB</i>					
Losses ($E[X] < 0$)	<i>AA</i>	95	21	9	110	Losses ($E[X] < 0$)	<i>AA</i>	351	48	16	245		
	<i>AB</i>	14	5	6	20		<i>AB</i>	20	14	4	33		
	<i>BA</i>	16	6	7	22		<i>BA</i>	17	2	3	18		
	<i>BB</i>	139	16	31	533		<i>BB</i>	78	14	13	174		

Table 5: Contingency Tables for Combined Domains of Risk and Preference Judgments

Although the predominant patterns of choice behavior are consistent with risk independence (see the top left and bottom right cells), there are some additional patterns of choice behavior that are also apparent (see the top right and bottom left cells). A significant number of subjects responded A_1A_2 (or B_1B_2) in the negative domain and B_1B_2 (or A_1A_2) in the positive domain. That is, some of the subjects changed their risk perceptions and preference when a lottery pair was transformed from the positive domain to the negative domain, which is inconsistent with the risk independence assumptions. In order to capture this form of choice behavior, the risk independence conditions can be generalized.

Assumption 5: Generalized risk independence for perceived risk. For $X', Y' \in P^0$, there exists some $w_0 \in Re$ such that $(w_0, X') \approx_R (w_0, Y')$, $(w_1, X') \succ_R (w_1, Y')$ for all $w_1 > w_0$, $(w_2, X') \prec_R (w_2, Y')$ for all $w_2 < w_0$ and $w_1, w_2 \in Re$.

Assumption 6: Generalized risk independence for preference. For $X', Y' \in P^0$, there exists some $w_0 \in Re$ such that $(w_0, X') \approx (w_0, Y')$, $(w_1, X') \succ (w_1, Y')$ for all $w_1 > w_0$, $(w_2, X') \prec (w_2, Y')$ for all $w_2 < w_0$ and $w_1, w_2 \in Re$.

These risk independence conditions are analogous to the generalized utility independence condition proposed by Fishburn and Keeney (1975). They basically lead to the same form of risk-value model (1) with a more generalized tradeoff factor $\phi(\bar{X})$. The generalized risk independence conditions will allow the tradeoff factor $\phi(\bar{X})$ to change its sign from positive to negative when the value of the mean changes.

An estimate of the point w_0 may vary for individuals whose preferences and risk judgments switch between domains, but we would expect it to be near zero for most of these individuals. Then the generalized risk-value model can be risk averse in the positive domain and risk seeking in the negative domain. In other words, this model could describe the choices of an individual who would switch her risk perception and preference for lotteries with a common mean when the mean changes from the positive domain to the negative domain.

In some early studies, Kahneman and Tversky (1979) found that subject risk attitudes and preferences shifted when a lottery pair moved across domains. Using a concave utility function for the standard measure of risk, the generalized risk-value model is consistent with the choice behavior described by the reflection effect.

In an experimental study regarding aspiration level effects on preference, Payne, Laughhunn, and Crum (1980, 1981) also found a reversal of choice between pairs of lotteries when adding or subtracting a constant amount from the original lottery pair. The generalized

risk-value model can largely explain their data when transformed lottery pairs have either all positive outcomes or all negative outcomes by using $\phi(\bar{X}) > 0$ when $\bar{X} > 0$ and $\phi(\bar{X}) < 0$ when $\bar{X} < 0$. If the aspiration level for a subject is not zero, the generalized risk-value model can also approximate their observed subject behaviors when the switching point w_0 is chosen to be close to this aspiration point.

The experiments provide empirical evidence regarding risk independence and generalized risk independence conditions for both risk perceptions and preference. As shown in Table 5, approximately 60% of subject choices in risk judgments and 50% of subject choices in preference judgments are consistent with the original risk independence assumptions (3 and 4). The generalized risk independence assumptions (5 and 6) provide models that will capture an additional 24% of subject choices in risk judgments and an additional 31% of subject choices in preference judgments.

6. Discussion

In this paper we have presented the results from an experiment to test the underlying axioms and assumptions of risk value theory, namely:

- Preference is the converse of risk for lotteries with $E[X] = 0$
- Utility theory describes preferences for lotteries with $E[X] = 0$
- Risk independence for risk judgments
- Risk independence for preference judgments

The data were consistent with the notion that preference is the converse of risk, and with the substitution axiom of utility theory for lotteries with zero mean. This study also supports risk independence for both preference and risk judgments. These conclusions are based on a limited

set of stimuli, but our objective of exploring all four of these issues limited the number of stimuli that could be presented to the subjects within a reasonable period of time.

The data also highlighted some additional patterns of choices indicating that the translation of lottery pairs from the positive domain to the negative domain often results in the reversal of preference and risk judgments. To capture this phenomenon, we have extended risk independence conditions to allow the tradeoff factor in the risk-value models to change sign, and therefore to infer risk aversion in the positive domain and risk seeking in the negative domain. These generalized risk-value models provide additional insights into the reflection effects (Kahneman and Tversky, 1979) and related empirical results (Payne, Laughhunn, and Crum, 1980, 1981).

Payne, Laughhunn, and Crum (1981) found that reversals of subject choices regarding lottery pairs with the equal means occurred more often when the outcomes of one lottery were all positive (or negative), but one outcome of the other lottery was negative (or positive). Then this particular outcome with the opposite sign of the mean became very salient to the subjects, which makes them more likely to use a heuristic focusing on this particular outcome instead of making a holistic judgment in their choices. When these lottery pairs were further transformed into the positive domain or the negative domain, reversals of subject choices actually were reduced (see their Table 1). This might have been due to the use of more holistic judgments by subjects for comparing these lotteries, since all outcomes of the lotteries are either positive or negative.

In this study, we used lotteries with multiple outcomes, which is more representative of real choice problems. Compared with other non-expected utility models, the risk-value models are particularly suitable to modeling decision problems with multiple outcome lotteries and continuous distributions. Under these choice situations, decision makers would be more

concerned about the overall shapes of possible outcome distributions than individual outcomes and probabilities (Allais, 1953, 1979; Lopes, 1984). Thus, they are more likely to make holistic judgments by summarizing the basic information associated with lotteries (e.g., mean value and perceived uncertainties or risk), and then consider tradeoffs between these summarized aspects.

The intuition of a risk-value trade is compelling. It provides additional insights into decision making under risk. Many previous studies show that people's choice can differ either because of differences in risk perceptions or because of differences in risk attitude. However, these concepts are usually confounded in expected and non-expected utility models. Weber and Milliman (1997) proposed the concept of perceived risk attitude that measures whether an individual tends to seek out alternatives perceived to be more risky (perceived risk seeking) or less risky (perceived risk averse). They showed that risk perception tended to change in harmony with choices, and that perceived risk attitude was remarkably constant for a given individual across situations or domains. The majority risk attitude (about 70-80%) was that of perceived risk aversion. Similarly in our study, 72% and 55% of subjects were consistent with perceived risk aversion in the gain domain and the loss domain respectively.

In a cross-cultural study, Weber and Hsee (1998) used a perceived risk-return model to investigate the relationship between risk perception, perceived risk attitude, and preference. The perceived risk attitude was measured by a constant tradeoff factor in their model. The risk-value model (1) provides additional flexibility for measuring and integrating risk perception, perceived risk attitude, and value. In particular, the tradeoff factor in model (1) is a function of mean, so the perceived risk attitude can be changed when the mean value of a lottery alters. Based on this study and previous results, the tradeoff factor should be positive (i.e., perceived risk aversion) for the majority of subjects.

In some situations, people may change their perceived risk attitude across domains, i.e., perceived risk averse in the positive domain and perceived risk seeking in the negative domain. The generalized risk independence conditions allow this switch by changing the sign of the tradeoff factor. This provides more flexibility in modeling people's perceptions of risk and preference.

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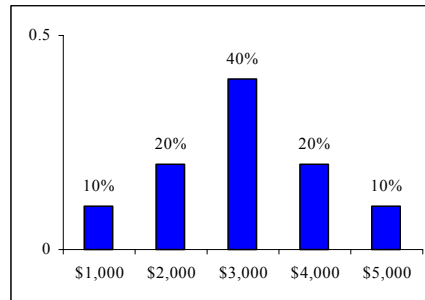
Appendix : Example of instructions for a risk judgment task

Thank you for agreeing to participate in this decision making study. We are interested in learning about two things. The first is what you think makes an option risky. We'll call this your "risk perception." The second is which of several potentially risky options you prefer. We'll call this your "preference." You will be asked to participate in both a RISK task (in which we ask about your risk perceptions) and a PREFERENCE task (in which we ask which options you prefer).

Before getting to the specifics, we'd like you to think about risk and preference in general. Things that we think are risky and things that we prefer to do (or not do) may be related, but they are not always the same (or opposite) thing. For example, most people agree that putting money in the stock market is "riskier" than putting money in a bank savings account. But people may have different preferences between these two options. Some people "prefer" to put money in the (risky) stock market, and others "prefer" to put money in a (less risky) bank savings account. Thus, the riskiness of an option does not necessarily tell us whether people prefer it or not. Sometimes people prefer options they think are risky because they think that the potential benefits (or payoffs) from the risky options outweigh their potential costs (or losses). But other times people prefer options they think are less risky because the potential benefits (or payoffs) of the risky options seem to be outweighed by their potential costs (or losses).

In the following experiments we will ask you to consider a set of lotteries or gambles. Some of the gambles involve winning money (positive dollar values), some involve losing money (negative dollar values), and some involve coming out even (positive and negative dollar values). For each lottery, imagine a jar containing 100 balls. Each ball has an amount of money to win or an amount to lose marked on it. The balls are well mixed in the jar and one of the balls will be chosen at random. You will win or lose the amount of money that is marked on that ball.

The picture to the right describes the contents of a sample jar. This jar has 10 balls marked with \$1,000, 20 balls marked with \$2,000, 40 balls marked with \$3,000, 20 balls marked with \$4,000, and 10 balls marked with \$5,000. Obviously, the more balls there are with an amount, the more likely this amount will be drawn from the jar.



In the RISK task, we are interested in knowing how you perceive the riskiness of various lotteries. You will be asked to compare lotteries in pairs regarding how risky they seem to you. Please note that in this RISK task, we are NOT asking you which of a pair of lotteries is more desirable or which prefer to play. Instead, we're asking you to tell us which of a pair of lotteries is relatively riskier. You will see two pairs of lotteries on each page. For each pair of lotteries, please tick the corresponding box to indicate which of the pair of lotteries that you think is relatively RISKIER. You can always refer back to your earlier judgments if you like. Please look at the presented information carefully. While there are no right or wrong answers we encourage you to think carefully about your responses.

For the preference task, the instructions were identical except that the text in the box above was replaced with :

In this PREFERENCE task, we are interested in knowing your judgment of the relative attractiveness or desirability of lotteries. You will be asked to compare each pair of lotteries in terms of your preference. So you need to make a choice between a pair of lotteries regarding which one you would prefer to play.

You will be presented two pairs of lotteries on each page. You need to tick the corresponding box to indicate which of the pair of lotteries that you would prefer to play if you have to. You can always refer back to your earlier judgments if you like. While there are no right or wrong answers we encourage you to think carefully about your response