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# The Value of a Statistical Life under Ambiguity Aversion

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# The Value of a Statistical Life under Ambiguity Aversion

## Abstract

We show that ambiguity aversion increases the value of a statistical life as soon as the marginal utility of wealth is higher if alive than dead. The intuition is that ambiguity aversion has a similar effect as an increase in the perceived baseline mortality risk, and thus operates as the “dead anyway” effect. We suggest, however, that ambiguity aversion should usually have a modest effect on the prevention of ambiguous mortality risks within benefit-cost analysis, and can hardly justify the substantial “ambiguity premium” apparently embodied in environmental policy-making.

JEL Code: D81, Q51, I18.

Keywords: ambiguity, value-of-a-statistical-life, uncertainty, risk-aversion, willingness-to-pay, benefit-cost analysis, environmental risk, health policy.

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## 1. Introduction

It is sometimes difficult to assess with precision the risks to health and life that we face. For instance, there is often conflicting information about the likelihood of dying from new environmental or technological risks. Remember the debates about the risks related to the mad cow disease or to the avian flu. Due to the scientific uncertainty over the channels of transmission of these diseases to human beings, it was difficult to predict the number of fatalities. Some experts predicted a few fatalities while other experts predicted several thousands of fatalities.

Another example that can illustrate the importance of uncertainty over the number of fatalities is the climate change problem. Climate change will increase worldwide mortality mostly from heat stress, malnutrition and vector-borne diseases. The World Health Organisation cited in the Stern review (2007) estimates that just a 1°C increase in global temperature could lead to at least 300,000 annual deaths from climate change (Stern, 2007, p. 75, part II). Yet, the exact increase in global temperature is highly uncertain, and so are the predictions about the number of deaths induced by climate change. This issue is important as worldwide mortality costs may account for more than half of the aggregate monetary-equivalent global warming damages estimate (IPCC, 1995, p. 198).

How do we react to the uncertainty over the probability of dying from a specific risk? In particular, do we behave as if we *average* the probabilities given by different experts (or different scenarios)? Or do we tend for instance to place excessive weight on the most

pessimistic one? The former is consistent with the standard expected utility approach, while the latter is more consistent with an approach that allows for an ambiguity aversion effect.

Since the seminal Ellsberg (1961)'s suggested experiment, it has been a fairly robust finding in experiments that subjects tend to be averse to ambiguity over probabilities (see, e.g., Camerer, 1995). The development of theories of ambiguity aversion is more recent. Some influential contributions include Gilboa (1987), Segal (1987), Schmeidler (1989), Gilboa and Schmeidler (1989), Klibanoff (2001), Epstein and Schneider (2003) and Klibanoff et al. (2005). These theories have been mainly applied to financial risks so far.<sup>1</sup> For example, Chen and Epstein (2002) suggest that ambiguity aversion might explain the equity premium puzzle.

There exist a few empirical analyses on ambiguity aversion when ambiguity concerns risks to life and health.<sup>2</sup> An example of such an analysis is Viscusi et al. (1991). They designed a survey in which participants were asked to choose between two living areas, A and B, where there is a risk of nerve disease due to environmental pollution. In the Area A, risks are ambiguous: one study indicated a risk level of 150 cases per 1 million population, and another study indicated a risk level of 200 per 1 million population. Participants then were asked what non-ambiguous risk in the Area B they would view as *equivalent* to the ambiguous risk posed in the Area A.

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<sup>1</sup> Some recent exceptions include the theoretical papers by Lange (2003) on climate change policy, Chambers and Melkonyan (2007) on the trade of toxic products and Albis and Thibault (2007) on savings behaviour in face of ambiguous longevity.

<sup>2</sup> Ritov and Baron (1990) develop a hypothetical experiment in which they show a reluctance to vaccination under missing information about side effects of the vaccine. Also, Riddle and Show (2006) show, using a survey of Nevada residents, a substantial effect of ambiguity concerning risks from nuclear-waste transport. Shogren (2005) reports a survey study about a food-borne illness posing ambiguous risks; see section 7 for more details.

The answers are reported in the Table 1 below. Notice that there was another treatment (treatment 2) in which the ambiguity concerning the risk in the Area A is increased: one study indicated 110 cases per 1 million population and another study indicated 240 cases per 1 million population (thus still with a mean risk of 175 cases per 1 million). Interestingly, Viscusi et al. (1991) show that survey participants do not simply average baseline mortality risks. In treatment 1, the mean of the answers about the equivalent risk is a bit greater than the mean risk and equal to 178.35, while in the more ambiguous treatment 2 the mean of the answers is equal to 191.08. Hence, this survey study seems to indicate that participants dislike ambiguity and dislike greater ambiguity.<sup>3</sup>

Treatment 1	Risk levels in Area A:	Mean of answers (sample size 65):
	[150, 200]	178.35
Treatment 2	Risk levels in Area A:	Mean of answers (sample size 58):
	[110, 240]	191.08

Table 1 – Survey data from Viscusi, Magat and Huber (1991)

This survey study raises another (unanswered) question: What is the willingness to pay to reduce the ambiguous risk? Indeed, ambiguity aversion is expected to have an effect on individuals' monetary-equivalents in face of change in ambiguous mortality risks. Consistent with benefit-cost analysis, ambiguity aversion may in turn have an effect on the choice of prevention policies concerning risks that are ambiguous. Our objective in this paper is to

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<sup>3</sup> A related effect is documented in Viscusi (1997). He presents to survey participants conflicting information about an environmental risk, and shows that participants treat the "high risk" information as being more informative.

understand this effect theoretically. More precisely, we study the theoretic impact of ambiguity aversion using a standard value of a statistical life (VSL) model.

We consider the recent theory of ambiguity aversion developed by Klibanoff et al. (2005) (hereafter KMM), that encompasses most common theories of ambiguity cited above. Also, this theory introduces a simple and interpretable measure of ambiguity aversion.<sup>4</sup> We show that the existence of ambiguity over baseline mortality risks increases the VSL when the decision maker is averse to ambiguity. This result holds as soon as the marginal utility of wealth of the decision maker is higher when he is alive than when he is dead, a standard assumption in mortality risk models. The intuition for the result is that the ambiguity aversion effect operates as the “dead anyway” effect (Pratt and Zeckhauser, 1996). Namely, the effect of ambiguity aversion on the VSL is similar to that of a perceived increase in the baseline mortality risk. Before turning to the presentation of the model and to the derivation of the results, we briefly discuss risk policy-making in the presence of ambiguity.

## **2. Ambiguous Risks and Policy-making**

Some policy analysts have suggested that decision-makers tend to put more effort into reducing ambiguous risks compared with familiar risks. A strand of the risk policy literature has shown that risk policy-making is plagued with a conservatism bias. This has often been presented as an “irrational” response of policy-makers.

Viscusi (1998) for instance argues that policy-makers err on the side of being too stringent when they face ambiguous risks, as exemplified by the higher regulation of synthetic

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<sup>4</sup> As we will see, this theory achieves a separation between ambiguity and ambiguity attitude. Besides, this theory is fairly tractable because preferences are “smooth” (and not “kinked”), and can easily be extended to state-dependent preferences (Nau, 2006).

risks compared to more familiar but often more severe carcinogens. Viscusi (1998) also explains how US Environmental Protection Agency (EPA) inflates risk cut-off values for individual risk-exposure by computing a theoretical “maximally exposed” individual (combining maximal ingestion rates, maximal exposure duration and minimal body weights). US EPA also typically uses upper bound values (like the 95% percentile) of probability distributions, and routinely applies rule-of-thumb margins of safety.<sup>5</sup> Obviously these practices do not reflect the mean tendency of the risk but instead bias the risk cut-off toward conservatism. Moreover, when several parameters are uncertain, risk assessment can be severely distorted due to the combination of several upper bound values. Belzer (1991) computed for instance that the excess mean risk due to dioxin was overestimated by about 5000 times by US EPA. As Viscusi and Hamilton (1999) suggest: “[t]hese biases, in effect, institutionalize ambiguity aversion biases” (Viscusi and Hamilton, 1999, p. 1013). Along similar lines, Sunstein (2000) argues that, in the presence of divergent risk scenarios, policy-makers focus too much on the worst-case scenario, and do not account enough for the low probabilities involved. More generally, Sunstein (2005) argues that risk regulatory decisions based on a precautionary principle approach are usually inconsistent with basic principles of economic efficiency.

Interestingly, most regulations issued by US EPA have a high implicit cost per life saved: the cost per life saved is usually larger than \$10 million (Viscusi, 1998), and often a much larger figure is reached in the range of hundreds of millions, or even billions dollars as was the case for the Superfund program (Viscusi and Hamilton, 1999). In contrast, revealed and stated preferences studies in developed countries in general obtain an individual VSL

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<sup>5</sup> Relatedly, Adler (2007) discusses for instance what he calls the “de minimis” risk. A “de minimis” risk is a risk cut-off, such as the incremental  $1 \times 10^{-6}$  lifetime cancer risk for air pollutants, or the 100-year-flood or the 475-year-earthquake for natural hazards. Adler argues that risk cut-offs are usually instrumental for defining policy objectives. Moreover, a recurrent problem is that risk cut-offs are usually extremely low, leading to extremely high safety standards, without a careful consideration of the economic costs of these standards.

ranging from \$1 to \$10 million (Viscusi and Aldy, 2003). These observations suggest that environmental risks may have been over-regulated. In addition, some empirical analyses have shown that environmental risks are far more regulated than health, occupational and transportation risks (Tengs et al., 1995; Tengs and Graham, 1996; Hahn, 1996). As many environmental risks may be more ambiguous risks than other risks, the “ambiguity premium” apparently embodied in policy-making is a good candidate to explain part of the observed over-regulation of environmental risks.

Benefit-cost analysis is sometimes presented as a possible “corrector” for inconsistencies in risk regulation. It may in particular help insulate risk policies from too much ambiguity aversion (Viscusi, 1998; Sunstein, 2002). Nevertheless, benefit-cost analysis is based on individuals’ VSL. Hence, if values obtained for individuals’ VSL embody ambiguity aversion, policy choices should somehow reflect individuals’ ambiguity aversion as well. This raises the following questions for policy-making. Are the observed individuals’ VSL mean estimates (usually ranging from \$1 to \$10 million) reflective of any form of ambiguity aversion? Should we use these VSL estimates to compute the social benefits of reducing *ambiguous* risks?

There is little rationale to answer positively to these questions. In effect, we observe that VSL estimates are usually obtained either from revealed preferences studies, most often using wage risk differential studies or road safety studies, or from stated preferences, most often using contingent valuation studies (for literature surveys, see, e.g., Viscusi and Aldy, (2003) Dionne and Lanoie (2004) and Andersson and Treich (2008)). However, occupational or road safety risks may arguably involve in average less ambiguity compared to most regulated environmental risks. Moreover, contingent valuation studies usually present

objective probabilities to respondents, and thus do not account for ambiguity either. Consequently, estimated VSL usually do not seem to capture an “ambiguity premium”. This may lead to under-estimate the values of the VSL that are applied to the reduction of ambiguous risks. The objective of the paper is, in a sense, to study this last argument.

### 3. The Value of a Statistical Life Model

Let us first introduce the VSL concept through an example. Consider a society composed of 100,000 identical individuals. They each face a (non-ambiguous) annual mortality risk of 100 in a 100,000. A public prevention program is expected to reduce this risk from 100 to 80 fatalities. Moreover, it is known that each individual is willing to pay \$500 for benefiting from this risk reduction program. In this example, the VSL would be equal to \$2.5 million. Indeed one could collect \$50 million in this society to save 20 statistical lives, hence a \$2.5 million per statistical life. Observe also the VSL is equal to the individual change in wealth (\$500) divided by the individual change in risk (20/100,000). Hence the VSL captures the trade-off between a change in wealth and a change in mortality risks.

We now introduce the standard static VSL model. An individual maximizes a (state-dependent) expected utility given by

$$V = (1 - p_0)u(w) + p_0v(w) \quad (1)$$

where  $p_0 \in [0,1]$  is the initial probability of dying, or the baseline risk,  $u(\cdot)$  is the utility of wealth if the individual survives the period, and  $v(\cdot)$  is the utility of wealth if the individual dies, that is, the utility of a bequest. We assume that  $u > v$ , and  $u' \geq v' \geq 0$ . This model was introduced by Drèze (1962), Jones-Lee (1974) and Weinstein et al. (1980) and has been

commonly used in the literature on the economic valuation of risks to health to health and life (e.g., Viscusi and Aldy, 2003).

Theoretically, the VSL is defined by the marginal rate of substitution between wealth  $w$  and baseline risk  $p_0$ . It thus captures this tradeoff between a change in wealth and a change in mortality risks. Assuming that  $u$  and  $v$  are differentiable, we thus get the VSL by a total differentiation of (1):<sup>6</sup>

$$\text{VSL}_0 \equiv \frac{dw}{dp_0} = \frac{u(w) - v(w)}{(1 - p_0)u'(w) + p_0v'(w)}. \quad (2)$$

Observe that the VSL may vary across individuals since it depends on  $w$ ,  $p_0$  and also on the shape of the utility functions through  $u$  and  $v$ .

In this model, the VSL increases with an increase in the baseline risk (see, e.g., Weinstein et al., 1980). Indeed in (2) an increase in  $p_0$  reduces the value of the denominator (since  $u' \geq v'$ ), and thus increases the VSL. That is, the marginal cost of spending money decreases when the baseline risk increases. This effect has been coined the “dead-anyway effect” (Pratt and Zeckhauser, 1996; see also Breyer and Felder, 2005). Some empirical evidence that the VSL increases with the baseline risk may be found in Horowitz and Carson (1993) and Persson et al. (2001). Notice that the dead-anyway effect can be potentially important in magnitude for a large baseline risk  $p_0$ . Indeed, assuming there is no bequest motive ( $v = 0$ ), the VSL in (2) tends to infinity when  $p_0$  tends to one. Intuitively, an individual facing a large probability of death has little incentive to limit his spending on

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<sup>6</sup> The VSL may also be viewed as the first-order approximation of the willingness to pay for a mortality risk reduction. Indeed, let the willingness to pay  $C_0(z)$  for a risk-reduction  $z$  is defined by  $(1 - p_0 + z)u(w - C_0(z)) + (p_0 - z)v(w - C_0(z)) = (1 - p_0)u(w) + p_0v(w)$ . We obviously get  $\text{VSL}_0 = C_0'(0)$ .

mortality risk reduction since he is unlikely to survive, and thus to have other opportunities for consumption.

#### 4. The Effect of Ambiguity Aversion

In the example above the annual baseline risk was unambiguous and equal to 100 in 100,000. Suppose now that the baseline mortality risk is ambiguous (but of the same magnitude). Suppose for instance that the decision-maker believes that with equal probability either 50 or 150 individuals are expected to die out of the 100,000 individuals in this society. How does this ambiguity over the baseline risk affect the decision-maker's VSL? Clearly, if the decision-maker maximizes standard expected utility, the VSL is not affected by ambiguity as the (expected) baseline risk equals 100 in 100,000 in both situations. But what does happen if the decision-maker is ambiguity averse? Does it change the VSL, and consequently does it change the social benefits that should be imputed to this prevention program?

To study analytically this question, we consider the KMM (2005)'s model of ambiguity attitude. Formally, and adapting the model above, the decision maker's utility is now written

$$W = \phi^{-1}\{E\phi\{(1-\tilde{p})u(w) + \tilde{p}v(w)\}\} \quad (3)$$

in which  $\tilde{p} \equiv p_0 + \tilde{\varepsilon}$  is a positive random variable that represents the ambiguity over the baseline mortality risk, and  $E$  denotes the expectation operator over the random variable  $\tilde{\varepsilon}$ , with  $E\tilde{\varepsilon} = 0$ . We assume  $\tilde{p} \in [0,1]$ . A natural interpretation of this model is that there is a two-stage lottery, first a lottery which determines one's baseline mortality risk  $\tilde{p}$ , and second a lottery which determines whether one is alive or dead. In short, KMM (2005) assume that preferences over these two lotteries are (subjective) expected utility preferences, although

permitting a different risk attitude towards each lottery,<sup>7</sup> giving rise to the expression (3) with the form of an “expected utility of an expected utility”.

The novelty in model (3) compared to model (1) is the introduction of the increasing function  $\phi$  which captures the attitude towards ambiguity. More precisely, the decision-maker has ambiguity averse (seeking) preferences if and only if  $\phi$  is concave (convex), as shown by KMM (2005). In this framework, similar to the usual financial risk aversion which is captured by the concavity of the utility function  $u$ ,  $\phi$  captures the attitude towards ambiguity. Assuming differentiability,  $\phi'' < 0$  thus represents strict ambiguity aversion. Two important particular cases of this model are constant ambiguity aversion,  $\phi(x) = (1 - \exp(-\alpha x)) / \alpha$ , and ambiguity neutrality,  $\phi(x) = x$ . KMM (2005)’s model yields Gilboa and Schmeidler (1989)’s well-known maxmin ambiguity model as a limiting case for infinitely ambiguity averse decision makers ( $\alpha \rightarrow \infty$ ).<sup>8</sup> But, in contrast to the Gilboa and Schmeidler’s framework, the KMM’s model distinguishes ambiguity (over a set of probability distributions) and ambiguity attitude.

Observe that under a concave  $\phi$ , utility  $W$  in (3) is reduced in the presence of ambiguity over baseline mortality risks. An implication of this observation is that the willingness to pay  $C$  to *eliminate* the mortality risk, defined by  $u(w - C) = W$ , is always

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<sup>7</sup> Hence, KMM (2005) assume a unique subjective belief over the first-stage lottery, but relaxes the reduction axiom and thus weights the probabilities nonlinearly (see Segal, 1987; see also section 11). What does happen if the decision-maker faces *objective* lotteries, i.e., if he knows objectively the distribution of  $\tilde{p}$ ? The answer seems open to two different interpretations. First, if the decision-maker faces objective lotteries it seems that there is no behavioral reason to expect that the reduction axiom does not apply between both lotteries, so that we are back to expected utility maximization. Second, having a strictly formal interpretation of KMM (2005)’s theory, both lotteries are different mathematical concepts and it is possible that to expect a different attitude towards the first and the second stage lottery, even though both lotteries involve objective probabilities. This second interpretation is fairly consistent with Halevy (2007)’s experimental data.

<sup>8</sup> Ju and Miao (2007) observe that, assuming  $\phi(x) = (1 - \exp(-\alpha x)) / \alpha$ , the ambiguity aversion model is strongly connected to the robust control theory (Hansen and Sargent, 2008).

higher under ambiguity aversion than under ambiguity neutrality. However, this result does not permit to conclude as to the effect of ambiguity for infinitesimally small mortality risk changes, as usually considered in the VSL literature.

The natural extension of the VSL under ambiguity and ambiguity aversion is obtained by a total differentiation of (3):<sup>9</sup>

$$\text{VSL}_A \equiv \frac{dw}{dp_0} = \frac{(u(w) - v(w))E\phi'\{(1 - \tilde{p})u(w) + \tilde{p}v(w)\}}{E((1 - \tilde{p})u'(w) + \tilde{p}v'(w))(\phi'\{(1 - \tilde{p})u(w) + \tilde{p}v(w)\})} \quad (4)$$

Notice that, although we assume that there is ambiguity over baseline risks, there is no ambiguity about the (infinitely small) risk change faced by the individual. Notice also that without ambiguity aversion (or under expected utility), that is under  $\phi'$  constant, we would get

$$\text{VSL}_0 = \frac{u(w) - v(w)}{E((1 - \tilde{p})u'(w) + \tilde{p}v'(w))} \quad (5)$$

which is strictly equal to the expression in (2) since  $E\tilde{p} = p_0$ .

Our objective is to use this framework to examine the effect of ambiguity aversion on the VSL. Comparing (4) and (5), it is immediate that the VSL is higher with ambiguity aversion than with ambiguity neutrality if and only if the following inequality holds:

$$E((1 - \tilde{p})u'(w) + \tilde{p}v'(w)) \times E\phi'\{(1 - \tilde{p})u(w) + \tilde{p}v(w)\} \geq E((1 - \tilde{p})u'(w) + \tilde{p}v'(w))(\phi'\{(1 - \tilde{p})u(w) + \tilde{p}v(w)\}).$$

This last inequality holds true if and only if the following covariance is negative, that is  $\text{COV}((1 - \tilde{p})u'(w) + \tilde{p}v'(w), \phi'\{(1 - \tilde{p})u(w) + \tilde{p}v(w)\}) \leq 0$ . Hence, using the covariance

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<sup>9</sup> Let us define again the willingness to pay  $C_1(z)$  for a risk-reduction  $z$  by the following equality  $E\phi\{(1 - \tilde{p} + z)u(w - C_1(z)) + (\tilde{p} - z)v(w - C_1(z))\} = E\phi\{(1 - \tilde{p})u(w) + \tilde{p}v(w)\}$ . We then have  $\text{VSL}_A = C_1'(0)$ .

rule,<sup>10</sup> if and only  $\phi'$  is decreasing, assuming  $u' \geq v'$ . Hence, provided death reduces the marginal utility of wealth compared to life, ambiguity aversion always reduces the VSL.<sup>11</sup> This is the main result of the paper. Notice that this result directly extends to an increase in ambiguity aversion in the sense defined by KMM (2005): a “more concave”  $\phi$  always leads to increase VSL (see the appendix for the derivation of this result).

## 5. An Intuition based on the Dead-anyway Effect

As we said in the introduction, the intuition for the result is based on the dead-anyway effect. To see this, let us consider for simplicity a discrete distribution of baseline mortality risks. Assume so that the random baseline risk  $\tilde{p}$  takes a value  $p_i$  with a probability  $q_i$ , with  $\sum_{i=1}^n q_i = 1$  (hence  $E\tilde{p} = \sum_{i=1}^n q_i p_i = p_0$ ). Let us then rewrite the VSL under ambiguity aversion

$$\text{VSL}_A = \frac{(u(w) - v(w))}{\hat{E}((1 - \tilde{p})u'(w) + \tilde{p}v'(w))} \quad (6)$$

where the operator  $\hat{E}$  is taken with respect to the *new* probability distribution of the baseline mortality risks given by :

$$\hat{q}_i = \frac{q_i \phi' \{ (1 - p_i)u(w) + p_i v(w) \}}{E\phi' \{ (1 - \tilde{p})u(w) + \tilde{p}v(w) \}} \text{ for all } i = 1, \dots, n \quad (7)$$

Then, using the covariance rule again for discrete random variables, it is straightforward to show that  $\hat{E}\tilde{p} \geq E\tilde{p}$  if and only if  $\phi$  is concave.

<sup>10</sup> Assume that  $f(p)$  is increasing in  $p$ . The covariance rule states that  $\text{COV}(f(\tilde{p}), g(\tilde{p})) \leq 0$ , that is  $Ef(\tilde{p})Eg(\tilde{p}) \geq Ef(\tilde{p})g(\tilde{p})$ , for all  $\tilde{p}$  if and only if  $g(p)$  is decreasing. See, e.g., Kimball (1951).

<sup>11</sup> Notice that we compared two different individuals, an ambiguity averse individual and an ambiguity neutral individual, keeping the level of ambiguity the same. Consider now only an ambiguity averse individual, but instead vary the level of ambiguity. Assume that in one situation there is ambiguity over baseline mortality risk and that in the other there is no ambiguity in the sense that the probability is known to be equal to  $p_0 (= E\tilde{p})$ . Then it is easy to show, using a similar demonstration, that ambiguity over probabilities reduces the VSL under  $u' \geq v'$ . In other words, VSL is higher under ambiguity than under no ambiguity.

Ambiguity over baseline mortality risks thus leads the ambiguity averse decision maker to behave in a way that is consistent with a perceived increase of a baseline mortality risk, from  $E\tilde{p}$  to  $\hat{E}\tilde{p}$ . In other words,  $\hat{E}\tilde{p}$  is the *certain* baseline risk so that the decision maker has the same VSL as in the ambiguous case. Technically, a new probability  $\hat{q}_i$  is associated to each baseline mortality risk  $p_i$ ,  $i = 1, \dots, n$ . Compared to the initial probability  $q_i$ , observe that the new probability  $\hat{q}_i$  is actually “weighted” by the quantity  $\omega_i \equiv \phi' \{ (1 - p_i)u(w) + p_i v(w) \} / E\phi' \{ (1 - \tilde{p})u(w) + \tilde{p}v(w) \}$ . Importantly, notice that this weight is larger the larger  $\phi' \{ (1 - p_i)u(w) + p_i v(w) \}$  is, that is, the larger  $p_i$  is. In other words, the new probability  $\hat{q}_i$  attributes respectively more weight to larger baseline risks. Notice also that this weight which affects the perceived increase in the baseline risk depends on individual characteristics  $(\phi, u, v, w)$ .

This intuition helps understand why the condition  $u' \geq v'$  is instrumental for ambiguity aversion to have a positive effect on VSL. Indeed the “dead anyway” effect rests on the assumption that wealth has a higher marginal value if alive than dead. This assumption seems sensible, and is usually accepted without much discussion. Nevertheless, this suggests that similar results cannot usually be obtained for pure financial risks. Indeed, under risk-averse preferences, the marginal utility is higher in the bad state than in the good state. This would basically reverse the result we obtained.<sup>12</sup> Along these lines, the effect of ambiguity over baseline risks to *health* (nonfatal risks) would also depend on how health status affects

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<sup>12</sup> Let  $v(w) = u(w - L)$  and assume that the financial loss  $L$  is positive. Then  $v'(w)$  is larger than  $u'(w)$  under  $u$  concave. Our result then tells us that the willingness to pay for a small reduction in the (ambiguous) probability of loss is reduced, and not increased, under ambiguity aversion. Our intuition for this (perhaps surprising) result is that a higher willingness to pay would further decrease the final wealth in the case of loss. This effect is disliked by risk-aversers, and has precisely more weight under ambiguity aversion.

the marginal utility of consumption. Indeed if health status increases the marginal utility of wealth (see, e.g., Viscusi and Evans, 1994), then our result carries over.

## 6. Equivalent Certain Baseline Mortality Risks

In the introduction, we mentioned the survey study developed by Viscusi et al. (1991). This study asked respondents to state the *certain* baseline risk they would judge as equivalent to the ambiguous risk they face. We coin it the “utility-equivalent” certain baseline risk. Formally, let us denote  $\bar{p}$  this utility-equivalent baseline risk; it is given by the following equation:

$$(1 - \bar{p})u(w) + \bar{p}v(w) = \phi^{-1}\{E\phi\{(1 - \tilde{p})u(w) + \tilde{p}v(w)\}\} \quad (8)$$

Obviously under  $\phi$  concave we have  $\bar{p} \geq E\tilde{p}$ . One may then wonder how  $\bar{p}$  compares to the “VSL-equivalent” baseline risk that we derived in the previous section, that we now denote  $\hat{p} \equiv \hat{E}\tilde{p} \geq E\tilde{p}$ . After simple manipulations, it is easy to see that

$$(1 - \hat{p})u(w) + \hat{p}v(w) = \frac{E((1 - \tilde{p})u(w) + \tilde{p}v(w))\phi'\{(1 - \tilde{p})u(w) + \tilde{p}v(w)\}}{E\phi'\{(1 - \tilde{p})u(w) + \tilde{p}v(w)\}} \quad (9)$$

so that we get  $\hat{p} \geq \bar{p}$  if and only if

$$\phi^{-1}\{E\phi\{(1 - \tilde{p})u(w) + \tilde{p}v(w)\}\} \geq \frac{E((1 - \tilde{p})u(w) + \tilde{p}v(w))(\phi'\{(1 - \tilde{p})u(w) + \tilde{p}v(w)\})}{E\phi'\{(1 - \tilde{p})u(w) + \tilde{p}v(w)\}} \quad (10)$$

for all  $\tilde{p}$ ,  $u$  and  $v$ . This last inequality is thus equivalent to

$$\phi^{-1}\{E\phi\{\tilde{x}\}\} \geq \frac{E\tilde{x}\phi'\{\tilde{x}\}}{E\phi'\{\tilde{x}\}} \text{ for all } \tilde{x}. \quad (11)$$

We now show that this inequality always holds true under  $\phi$  concave. To do so, we use a result derived in Watt (2008). Let the following function  $g(\lambda) = E\phi\{\lambda\hat{x} + (1-\lambda)\tilde{x}\}$  with  $\hat{x}$  being the certainty equivalent of  $\tilde{x}$ , or  $\phi\{\hat{x}\} = E\phi\{\tilde{x}\}$ . Since  $g(\lambda)$  is concave in  $\lambda$  under  $\phi$  concave, we have  $g(\lambda) \geq \lambda g(0) + (1-\lambda)g(1) = g(0)$  for any  $\lambda \in [0,1]$ . Thus we must have  $g'(0) \geq 0$ , which is equivalent to inequality (11).

We have thus shown that the utility-equivalent certain baseline risk is always lower than the VSL-equivalent certain baseline risk. An illustration of this result may be provided using Viscusi et al. (1991)'s survey study. Remember that subjects participating in treatment 2 judged the certain 191 in 1 million risk to be equivalent to an ambiguous risk of either 110 or 240 in 1 million risk. Then, the theoretical result just derived predicts that those subjects are expected to have a VSL in the ambiguous risk case to be at least *greater* than the VSL obtained with a certain 191 in a million baseline risk (and even if the mean of the baseline risk is equal to only 175 in a million).

We have thus shown that ambiguity aversion increases the VSL. Also, we have derived a result useful to compute a lower bound for the VSL in the ambiguous risk case. This suggests that ambiguity aversion may possibly have an important effect on the VSL. However, in the next section, we will suggest using a numerical illustration that the effect of ambiguity aversion should be in general rather limited.

## 7. A Numerical Illustration

The few empirical papers dealing with ambiguity over risks to life and health mentioned in the introduction did not elicit monetary equivalents. The only study to do so

(that we are aware of) is a survey study mentioned in Shogren (2005) about a food-borne pathogen, *Salmonella*. This survey study compares monetary equivalents for risk elimination under non-ambiguous and ambiguous probabilities scenarios. Interestingly, Shogren (2005) reports that “mean willingness-to-pay responses were higher for ambiguous versus unambiguous scenarios for all probabilities for food safety, but these differences were not significantly different. This survey has provided evidence that people prefer unambiguous risks for food safety, but not enough to generate a significant difference” (Shogren, 2005, p. 125-26).

We will now briefly illustrate our theoretic result using some of the figures reported in Shogren (2005). We also use some arbitrary utility functions and parameters. We first assume a constant relative risk aversion utility function  $u(w) = w^{1-\gamma}(1-\gamma)^{-1}$  with  $\gamma \in [0,1[$ , and no bequest motive, that is  $v = 0$ .<sup>13</sup> In that case, the VSL is simply equal to  $w(1-\gamma)^{-1}(1-p_0)^{-1}$ . To illustrate, if we take a square root utility function  $u(w) = \sqrt{w}$  and a lifetime wealth of \$1 million, the VSL equals \$2 million for a zero baseline risk. Notice also that the VSL increases nonlinearly with this baseline risk. As we said above, the VSL tends to infinity when  $p_0$  tends to 1, truly the “dead anyway” effect. We thus expect the effect of ambiguity aversion to strongly depend on where the baseline risk is located.<sup>14</sup> Finally, we will assume a constant ambiguity aversion, that is  $\phi(x) = (1 - \exp(-\alpha x))/\alpha$  for  $\alpha > 0$  (and  $\phi(x) = x$  for  $\alpha = 0$ ).

We further assume, as in one treatment of the study reported in Shogren (2005), that the baseline mortality risk is either equal to  $p_1 = 1/666$  or to  $p_2 = 1/2000$  with equal

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<sup>13</sup> Parameter  $\gamma$  less than 1 guarantees  $u > v$ .

<sup>14</sup> Using the expression  $w(1-\gamma)^{-1}(1-p_0)^{-1}$  for the VSL, notice that the elasticity of the VSL with respect to the baseline risk is equal to  $p_0/(1-p_0)$ , and thus strongly varies depending on whether  $p_0$  is close to 0 or 1.

probability. We thus have  $E\tilde{p} = 1/1000$ . With these values, we obtain for instance  $\hat{E}\tilde{p} = 1.23/1000$  for  $\alpha = 0.5$ . Moreover,  $\hat{E}\tilde{p}$  tends asymptotically to  $1/666$  for  $\alpha$  large; namely, under extreme ambiguity aversion the decision maker will behave as if he would face the “worst-case” baseline mortality risk. Interestingly, in this example the impact of ambiguity aversion on the VSL is always modest, even under extreme ambiguity aversion. Indeed, a change from  $E\tilde{p} = 1/1000$  to  $\hat{E}\tilde{p} = 1/666$  leads to an increase of the VSL (of about \$2 million) by a mere \$1000. Notice that this numerical illustration is consistent with the results of a modest effect of ambiguous probabilities reported in Shogren (2005).

In contrast, assume that the baseline mortality risk is either very high and equal to  $p_1 = 1/2$  (i.e., a 50% chance of dying!) with a small  $1/999$  probability, or equal to  $p_2 = 1/2000$ . Notice that we still have  $E\tilde{p} = 1/1000$ . For these new values, we obtain that  $\hat{E}\tilde{p}$  is (almost) equal to  $1/2$  for  $\alpha = 0.5$ , and so is the case for higher values of  $\alpha$ . Hence, the effect is similar to an increase from  $E\tilde{p} = 1/1000$  to  $\hat{E}\tilde{p} = 1/2$ . The VSL thus almost doubles due to an ambiguity aversion effect. Consequently, the possibility of a high baseline mortality risk, even if this possibility is very unlikely, may significantly increase the VSL.

This numerical exercise based on arbitrary functional forms and arbitrary parameters suggests that the effect of ambiguity aversion is usually modest, unless there is a possibility of an extremely high baseline mortality risk, combined with a large ambiguity aversion. We believe that this insight should carry over in most “regular” numerical exercises. Indeed, the usual modest effect of ambiguity aversion on the VSL is due to the limited impact of the baseline mortality risk on the VSL in general. In other words, ambiguity aversion is expected to have usually a modest impact on the VSL because the dead-anyway effect is usually small

(unless the probability of death is extraordinary high). We are thus tempted to conclude that ambiguity aversion can hardly justify *a priori* the very high implicit cost per life saved of some public environmental programs (e.g., several hundreds of millions dollars per life saved), even accounting for the fact that these public programs can reduce ambiguous risks.

## 8. Differentiated Risk Changes

We assume in this section that there are  $n$  equally likely baseline mortality risks  $p_i$ ,  $i=1,...,n$ , with  $p_1 \geq p_2 \geq ... \geq p_n$ . The decision maker's utility is then given by

$$\phi^{-1}\left\{\frac{1}{n}\sum_{i=1}^n\phi\{(1-p_i)u(w)+p_iv(w)\}\right\} \quad (12)$$

The previous analysis assumed that a (infinitesimal) risk change applies uniformly to all  $p_i$ s (through a reduction of  $p_0$  in  $p_i = p_0 + \varepsilon_i$ ). This may be viewed as somehow restrictive, as risk changes might possibly affect *differently* each possible baseline mortality risk  $p_i$ . We call a “differentiated risk change”, a change in risk that is different across the  $p_i$ s. An example of a differentiated risk change is a prevention measure such that the risk reduction is strictly positive when  $\tilde{p}$  is equal to  $p_1$ , and 0 otherwise. In this case, the prevention measure would be only efficient in the worst-case scenario leading to a reduction in the maximal baseline mortality risk.<sup>15</sup>

Notice first that, within the expected utility framework, only the change in the *expected* baseline mortality risk matters. Hence, a similar risk change applied differently to a low or to a large baseline mortality risk would have exactly the same monetary-equivalent

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<sup>15</sup> Another example is when an intervention reduces the risk by a constant fraction (e.g., if it reduces exposure to a risk by half).

value to the decision-maker. However, this need not be the case under ambiguity aversion. Technically, this is due to the fact that the objective in (12) is non-linear in the  $p_i$ s under ambiguity aversion.

To further study this problem, we denote  $VSL^i$  the marginal rate of substitution between wealth and the baseline mortality risk  $p_i$ ,<sup>16</sup> to get:

$$VSL^i \equiv \frac{dw}{dp_i} = \frac{(u(w) - v(w))\phi'\{(1-p_i)u(w) + p_iv(w)\}}{\sum_i ((1-p_i)u'(w) + p_iv'(w))(\phi'\{(1-p_i)u(w) + p_iv(w)\})} \text{ for } i = 1, \dots, n \quad (13)$$

The quantity  $VSL^i$  should be interpreted as the monetary-equivalent value associated to an infinitesimal change in risk *contingent* to the baseline mortality risk  $p_i$ . The expression of  $VSL^i$  is useful to understand how the decision maker would want the risk reduction to be differentiated, and to which extent this differentiation depends on ambiguity aversion. Indeed, it is immediate to obtain that the difference  $VSL^j - VSL^i$  has the sign of  $\phi'\{(1-p_j)u(w) + p_jv(w)\} - \phi'\{(1-p_i)u(w) + p_iv(w)\}$ , and is thus positive when  $p_j \geq p_i$  under ambiguity aversion.

Consequently, ambiguity aversion unsurprisingly leads the decision maker to value more a risk reduction contingent to the highest baseline mortality risk  $p_1$ , rather than any similar risk reduction contingent to another baseline mortality risk. Ambiguity aversion may thus rationalize a focus on the worst-case scenario in public prevention programs, even assuming a mild ambiguity aversion of the decision-maker. Notice, however, that a full examination of how the decision maker should optimally select the “differentiation” of risk

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<sup>16</sup> The notations are a bit loose here. Differentiating with respect to  $p_i$  means differentiating with respect to  $p_0$  in  $p_i = p_0 + \varepsilon_i$ , keeping all  $p_0$ s constant in all  $p_j, j \neq i$ .

changes across different baseline risks must take into account the relative cost of differentiation. In particular, it may be very costly (or not even technically possible) to allocate all units of prevention to the reduction of the highest baseline risk.

## 9. A Self-protection Model

We have studied so far how ambiguity aversion affects the monetary-equivalent value of a public prevention program. The objective of this section is to study how ambiguity aversion affects individual prevention choices. Intuitively, given that an individual who is ambiguity averse does always value more a marginal unit of prevention (implying a higher VSL) than an ambiguity neutral individual, we may expect that this individual should also select a higher level of prevention. We will show in this section that this intuition is not always correct.

To study individual prevention choices, we need to be more general about how individual prevention efforts lead to a risk reduction of the baseline mortality risks. We capture this by introducing the general function  $p_i(e)$ , that represents how the baseline mortality risk varies with the prevention effort. We assume that prevention effort decreases the baseline mortality risk  $p_i'(e) < 0$ , at a decreasing rate  $p_i''(e) \geq 0$ . The objective of the decision maker is to choose the prevention effort  $e$  to maximize

$$\phi^{-1}\left\{\sum_{i=1}^n q_i \phi\{(1-p_i(e))u(w-e) + p_i(e)v(w-e)\}\right\} \quad (14)$$

This is a simple state-dependent self-protection model with ambiguity aversion. It is easy to see that  $g_i(e) \equiv (1-p_i(e))u(w-e) + p_i(e)v(w-e)$  is concave in  $e$  under the assumption that  $u$  and  $v$  are concave, which implies that the program in (14) is concave as

well under this last assumption combined with ambiguity aversion. The first order condition characterizing the optimal  $e$  can be written as follows

$$\frac{(u(w-e) - v(w-e)) \sum_{i=1}^n q_i (-p'_i(e)) \phi' \{g_i(e)\}}{\sum_{i=1}^n q_i ((1-p_i(e)) u'(w-e) + p_i(e) v'(w-e)) \phi' \{g_i(e)\}} = 1 \quad (15)$$

It is easy to see then that ambiguity aversion raises the optimal prevention effort compared to ambiguity neutrality if and only if the left hand side of (15) is higher than the same expression assuming  $\phi'$  constant.

The numerator of the left hand side of expression (15) is the marginal benefit of prevention while the denominator is the marginal cost of prevention. Notice that since  $g_i(e)$  decreases with  $p_i(e)$ , the quantity  $\phi' \{g_i(e)\}$  always co-varies negatively with  $(1-p_i(e)) u'(w-e) + p_i(e) v'(w-e)$  in the denominator of (15) under  $\phi'$  decreasing and  $u' \geq v'$ . This implies that the marginal cost of prevention is always reduced under ambiguity aversion compared to under ambiguity neutrality. This is a general observation that holds true for any function  $p_i(e)$ . Nevertheless, the overall impact of ambiguity on the prevention effort is ambiguous since the effect of ambiguity aversion on the marginal benefit of prevention is unclear; this effect indeed depends on how  $p_i(e)$  co-varies with  $-p'_i(e)$ .

To illustrate, assume first that the baseline mortality risk takes an additive form, given by  $p_i(e) = p_i - r(e)$  (with  $0 \leq r(e) \leq p_i$  for  $i = 1, \dots, n$ ), so that the covariance between  $-p'_i(e)$  and  $p_i(e)$  is zero. Then, only the first negative effect on the marginal cost of prevention is at play. It is straightforward in that case to prove that ambiguity aversion always increases the prevention effort, under  $u' \geq v'$ . This result is essentially the same as the one obtained in section 4. Assume alternatively that the baseline mortality risk has a specific

multiplicative form, given by  $p_i(e) = 1 - \rho_i s(e)$  (with  $0 \leq \rho_i \leq 1/s(e)$  for  $i = 1, \dots, n$ ), and assume also that there is no bequest motive  $v = 0$ . Then, it is easy to show that (15) simply reduces to

$$\frac{u(w-e)s'(e)}{u'(w-e)s(e)} = 1 \quad (16)$$

Consequently, ambiguity aversion has strictly no effect on the prevention effort in this last case. The reduction of the marginal cost of prevention is exactly compensated by the increase of the marginal benefit. One intuition for this result under the multiplicative form is that an increase in the prevention effort, although reducing the expected baseline mortality risk, also increases the level of ambiguity faced by the individual. Formally, an increase in  $e$  increases the survival probability  $\rho_i s(e)$  (remember that  $s'(e) > 0$  by assumption), which is itself ambiguous. An increase in  $e$  thus operates as an increase in the spread of the ambiguity support in this case. In contrast, when the baseline mortality risk is additive a change in  $e$  does not affect the level of ambiguity.

The analysis of this self-protection model thus indicates that the VSL model that we studied before captures solely an aspect of the relationship between prevention motives and ambiguity aversion. In particular, we considered a specific model in which the initial situation was ambiguous but the effect of the actions of prevention were not ambiguous. In a more general model, ambiguity aversion may thus not systematically increase the value of a public prevention program that decreases an ambiguous risk if the effects of this program are themselves ambiguous.

## 10. An Alternative Characterization of Ambiguity Aversion

The above analysis has considered the KMM (2005)'s theory of ambiguity aversion that encompasses most existing ambiguity theories, introduces a measure of ambiguity aversion, and achieves a separation between ambiguity and ambiguity attitude. The recent Gajdos et al. (2007)'s theory of ambiguity also shares these fine properties, but is based on another axiomatics. The purpose of this section is to study whether our results extend to this alternative theory of ambiguity.

Under Gajdos et al. (2007)'s theory, the decision maker's utility can be written

$$(1-\alpha)(E((1-\tilde{p})u(w) + \tilde{p}v(w))) + \alpha((1-p_1)u(w) + p_1v(w)) \quad (17)$$

in which  $\alpha$  is the parameter of ambiguity aversion (or "imprecision aversion") and  $p_1$  still denotes the highest baseline mortality risk. This framework, already suggested by Ellsberg (1961, p. 664 and 665), thus considers a linear combination between the expected utility and the minimum of expected utility.

Using this formulation, we easily obtain

$$VSL_1 \equiv \frac{dw}{dp_0} = \frac{u(w) - v(w)}{(1-\alpha)(E(1-\tilde{p})u'(w) + \tilde{p}v'(w)) + \alpha((1-p_1)u'(w) + p_1v'(w))} \quad (18)$$

which is also equal to

$$VSL_1 = \frac{u(w) - v(w)}{(1-p^*)u'(w) - p^*v'(w)} \quad (19)$$

with  $p^* = (1-\alpha)E\tilde{p} + \alpha p_1$ . Notice that the equivalent certain baseline mortality risk  $p^*$  does not depend on individual characteristics (utility, wealth), except on the level of ambiguity aversion  $\alpha$ .

Most notably, it is then immediate that  $VSL_1$  increases with the parameter of ambiguity aversion  $\alpha$ , provided  $u' \geq v'$ . Consequently, in this framework as well, ambiguity aversion raises the VSL as soon as the marginal utility of wealth is higher if alive than dead. Moreover, the intuition is similar since ambiguity aversion effect also operates as the “dead anyway” effect, through a perceived change of the baseline risk from  $E\tilde{p} (= p_0)$  to  $p^*$ . Finally, it is immediate to see that there is no difference between the utility-equivalent baseline risk and the VSL-equivalent baseline risk, unlike in the previous framework based on the KMM (2005)’s theory of ambiguity aversion. This last observation may suggest a simple way to discriminate empirically between this theory and the KMM theory in the context of mortality risks.

## 11. Rank-dependent Expected Utility Models and Ambiguity Aversion

An important class of non-expected utility model is the rank-dependent expected utility (RDEU) model. This model generalizes (1):

$$g(1 - p_0)u(w) + (1 - g(1 - p_0))v(w) \quad (20)$$

in which  $g(\cdot)$  is continuous and strictly increasing with  $g(0) = 0$  and  $g(1) = 1$ ; it is usually coined the decision weight function (Quiggin, 1982; Yaari, 1987). When  $g(\cdot)$  is linear, we are back to the expected utility model (1). When  $g(\cdot)$  is convex, it can be shown that the decision-maker is averse to any mean-preserving spread of outcomes under a concave state-independent utility function (Chew et al., 1987). Under these preferences, the VSL equals<sup>17</sup>

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<sup>17</sup> See also Bleichrodt and Eeckhoudt (2006). It is not difficult to compare the VSL under the RDEU model to that under the expected utility model. Assume for instance that  $v(\cdot) = 0$ , then  $VSL_{RDEU}$  is higher than  $VSL_0$  if and only if that  $g'(x) \geq g(x)/x$ , that is  $g(x)/x$  increasing in  $x$ . This condition on the decision weight function is weaker than  $g(\cdot)$  convex, and corresponds to the notion of  $g(\cdot)$  “star-shaped at 0” defined in Chateauneuf et al. (2004).

$$\text{VSL}_{\text{RDEU}} \equiv \frac{g'(1-p_0)(u(w)-v(w))}{g(1-p_0)u'(w)+(1-g(1-p_0))v'(w)} \quad (21)$$

Segal (1987) builds on RDEU models to explain the Ellsberg's paradox. Segal was the first to suggest that an ambiguous lottery may be viewed as a two-stage lottery, where the first, imaginary, stage is over the possible values of  $p$ . More formally, Segal's preferences are based on two assumptions: first, Segal assumes that the decision-maker applies the RDEU model to any lottery, but second he relaxes the axiom of reduction of compound lotteries between the first-stage and the second-stage lottery.<sup>18</sup> Ambiguity aversion then reduces to a complex property on  $g(\cdot)$  (see Theorem 4.2, Segal, 1987, p. 185). Interestingly, Halevy (2007) observes that more than one third of subjects in his experiment seem to exhibit a pattern of choices consistent with Segal's preferences.

In the rest of this section, we show by an example that ambiguity aversion in the sense of Segal (1987) need not lead to an increase in the VSL. In this example, we assume that there are only two possible baseline risks  $p_1$  and  $p_2$  (with probability  $q_1$  and  $q_2$ ) assuming  $p_1 > p_2$ , and we also assume that there is no bequest motive. Under these assumptions, the utility under Segal's preferences reduces to

$$g(q_2)g(1-p_2)u(w)+(1-g(q_2))g(1-p_1)u(w) \quad (22)$$

We then compute the VSL under these preferences, to get:

$$\text{VSL}_s \equiv \frac{g(q_2)g'(1-p_2)u(w)+(1-g(q_2))g'(1-p_2)}{g(q_2)g(1-p_2)+(1-g(q_2))g(1-p_1)} \frac{u(w)}{u'(w)} \quad (23)$$

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<sup>18</sup> Segal (1987) observes that if a sufficiently long time passes between the two stages of the lottery, there is no reason to believe in the reduction axiom. A related interpretation of irreducibility of compound lotteries is that of a preference for a timing of resolution of uncertainty (see, e.g., Kreps and Porteus, 1978).

Then, we assume  $q_2 = 0.5$ ,  $p_0 = 0.5$  with  $p_1 = 0.5 + \varepsilon$  and  $p_2 = 0.5 - \varepsilon$ . Finally, we compute the difference between  $VSL_S$  and  $VSL_{RDEU}$  computed with  $g(p) = p^2$ . It is straightforward to obtain that this difference is equal to:

$$\frac{4(1-4\varepsilon)\varepsilon}{1-2\varepsilon+4\varepsilon^2} \frac{u(w)}{u'(w)} \quad (24)$$

which is positive, and then *negative* for some increasing values of  $\varepsilon$  in  $[0, 0.5]$ . The key point here is that  $g(p) = p^2$  is consistent with the conditions for ambiguity aversion exhibited in Segal (1987)'s Theorem 4.2. Hence, this example shows that ambiguity aversion may actually lead to reduce the VSL.

## 12. Risk Preferences and the VSL

This paper is not the first to analyze the theoretic effect of risk preferences on the VSL. Eeckhoudt and Hammitt (2004) show that financial risk aversion usually has an ambiguous effect on the VSL.<sup>19</sup> In contrast, we have shown that ambiguity aversion always increases the VSL. A simple implication of this observation is that effect of ambiguity aversion need not reinforce that of risk aversion (Gollier, 2006) to understand the tradeoff between money and mortality risks.

Studying the effect of risk preferences on the VSL is relevant both for revealed and stated preferences approach. It may permit for instance to better understand the self-selection bias induced by the revealed preferences approach when individuals make risk-exposure choices (e.g., living in a specific polluted area) posing ambiguous risks to life and health. Also, the VSL obtained from survey studies may be sensitive to the pieces of information that

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<sup>19</sup> We notice, however, that the classical Pratt (1964)'s concept of comparative risk aversion is not clear-cut under state-dependent preferences (Karni, 1983).

are delivered to participants in surveys. As shown by Viscusi et al. (1991), the communication of ambiguous risk information may have an effect on participants' responses. As a result, it may be interesting to estimate the effect of ambiguity aversion on the VSL obtained in future survey studies. More generally, it is important to better understand the economic consequences related to the behavioral responses of information policies about ambiguous risks.

A more fundamental question arises, however, when one compares the effect of risk aversion and that of ambiguity aversion. While risk aversion has long been considered as a part of the welfare of individuals, the same is not necessarily true for ambiguity aversion. It is known that some theories of ambiguity aversion may lead to time-inconsistent choices, to some conceptual difficulties in beliefs' updating and to a negative value of information. This may not be a problem for the descriptive power of ambiguity aversion theories, but this raises some legitimate concerns for benefit-cost analysis and more generally for welfare analysis.

A related policy argument is that the primary objective should be the reduction of the expected number of deaths. Yet, policy-makers could certainly save more lives by targeting familiar risks compared to ambiguous risks. Hence allowing for an ambiguity premium in policy-making may lead to a "statistical murder" (Graham, 1995). A classical counter-argument is that what should matter is the additional *welfare* gain induced by a safety policy, even if this policy does not maximize the total number of lives saved. It is indeed perfectly reasonable to argue that reducing the fear associated with ambiguous risks has a value for individuals, and that this value should be reflected in policy-making.<sup>20</sup>

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<sup>20</sup> Interestingly, Camerer et al. (2007), using the technique of fMRI (functional magnetic resonance imaging), show that subjects' brain areas like the amygdala are more active under the ambiguity conditions in their experiment. They go on to notice that the "amygdala has been specifically implicated in processing information related to fear" (Camerer et al., 2007, p. 131).

### **13. Conclusion**

Many mortality risks are ambiguous. The sources of ambiguity are multiple. They may include scientific uncertainty, conflicting expertise, problems of communication and credibility, or lack of information about individual heterogeneous risk exposures and differences in susceptibility (e.g., genetics). There is a need to better understand the economic implications of ambiguity aversion. In particular, it is known that emotional fearful situations, like life-threatening situations, may lead individuals to react to probabilities and outcomes in a manner that is different from that postulated by expected utility (see, e.g., Loewenstein, 2007). Ambiguity aversion may potentially play an important role in these situations. It may strongly affect the valuation of health and mortality risks changes.

We have demonstrated that ambiguity aversion increases the value of a statistical life. Ambiguity aversion may thus possibly justify the apparent “over-regulation” of some environmental risks. But how much “over-regulation” is justified? We urge to obtain better empirical estimates of individuals’ ambiguity aversion. Interestingly, our first numerical analysis suggests that the effect of ambiguity aversion should be small. This paper thus does not justify much over-regulation of ambiguous risks. It rather supports the view that we should “debias” risk regulatory decisions from too much ambiguity aversion. But, clearly, more theoretical and empirical research is needed on this topic in order to be more confident in this policy recommendation. More fundamentally, the welfare implications of the effects of ambiguity aversion should be discussed with great caution.

## Appendix: Comparative Ambiguity Aversion

The main result derived in the paper compares an ambiguity averse to an ambiguity neutral individual (or an expected utility maximizer). This appendix shows that this result extends to the notion of a comparison with a “more ambiguity averse” decision maker.

Consider two agents, 1 and 2. Assume that they share the same underlying state-dependent utility functions, the same wealth and the same risk beliefs. Assume that they are both ambiguity averse, with the concave functions  $\phi_k$ ,  $k=1,2$  denoting their respective ambiguity aversion. Following KMM (2005), agent 2 is said to be more ambiguity averse than an agent 1 if and only there exists an increasing and concave function  $T$  so that  $\phi_2 = T(\phi_1)$  in the relevant domain. Assuming  $T$  twice differentiable and concave, and using (4), we are done if we show that

$$\text{VSL}_1 = \frac{(u(w) - v(w))E\phi_1' \{ \cdot \}}{E((1 - \tilde{p})u'(w) + \tilde{p}v'(w))(\phi_1' \{ \cdot \})} \quad (\text{A1})$$

is lower than

$$\text{VSL}_2 = \frac{(u(w) - v(w))E\phi_1' \{ \cdot \} T'(\phi_1 \{ \cdot \})}{E((1 - \tilde{p})u'(w) + \tilde{p}v'(w))(\phi_1' \{ \cdot \} T'(\phi_1 \{ \cdot \}))} \quad (\text{A2})$$

where  $\phi_1' \{ \cdot \}$  stands for  $\phi_1' \{ (1 - \tilde{p})u'(w) + \tilde{p}v'(w) \}$ .

Using (7), notice that we can write

$$\text{VSL}_1 = \frac{(u(w) - v(w))}{\hat{E}((1 - \tilde{p})u'(w) + \tilde{p}v'(w))} \quad (\text{A3})$$

and

$$\text{VSL}_2 = \frac{(u(w) - v(w))\hat{E}T'(\phi_1 \{ \cdot \})}{\hat{E}((1 - \tilde{p})u'(w) + \tilde{p}v'(w))(T'(\phi_1 \{ \cdot \}))} \quad (\text{A4})$$

Moreover, notice then that comparing eqn. (A3) and eqn. (A4) is similar to comparing eqn. (5) and eqn. (4) where  $E$  is replaced by  $\hat{E}$  and  $\phi'$  is replaced by  $T'(\phi_1\{.\})$ . We are thus done if and only if  $T'(\phi_1\{.\})$  is decreasing in its argument provided  $u' \geq v'$ . And this is precisely the case if and only if  $T$  is concave. This shows that  $T$  concave is sufficient for the result. The necessity part of the proof is straightforward.

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