"The Value of a Statistical Life under Ambiguity Aversion"

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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.

Key Words: Ambiguity, Value-of-a-statistical-life, Uncertainty, Risk-aversion, Willingness-to-pay, Benefit-cost analysis, Environmental risks, Health policy.

JEL: D81, Q51, I18.

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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 fatalities.

Another example that can illustrate the importance of uncertainty over the expected number of fatalities is the climate change problem. Climate change will increase worldwide mortality 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 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 aggregate estimate of global warming (IPCC, 1995, p. 198).

How do we react to the uncertainty on the probability of dying from a specific risk? In particular, do we behave as if we *average* the probabilities given by different experts (or scenarios)? Or do we tend for instance to place excessive weight on the most pessimistic one? The former is consistent with the standard (subjective) 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 is a fairly robust finding in experiments that individuals are averse to ambiguity over probabilities. 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.[1] 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.[2] 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 150 cases per 1 million population, and another study indicated a risk level of 200 per 1 million population. Participants then were asked what risk in the Area B they would view as *equivalent* to the risk posed in the Area A.

[1] 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.

[2] 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.[3]

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

We consider the recent Klibanoff et al. (2005)'s theory of ambiguity aversion that encompasses most common theories of ambiguity cited above. Also, this theory introduces a simple and interpretable measure of ambiguity aversion.[4] 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.

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

[4] 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).

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 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.[5] 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: it is usually higher than $10 million (Viscusi, 1998), and often a much higher figure 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 a VSL 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 at 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 individuals’ VSL embody ambiguity aversion, policy choices should somehow reflect individuals’ ambiguity aversion as well. This raises the following important questions for policy-making. Are the observed individual VSL 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

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[5] 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 1×10^{-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 is usually extremely low. As a result, it may lead to target extremely high safety standards, without a careful consideration of the economic costs of these standards.

often using contingent valuation studies (Viscusi and Aldy, 2003; Dionne and Lanoie, 2004). 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 can reduce this risk from 100 to 80 expected 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

$$\mathrm{V}=(1-p_0)u(w)+p_0v(w) \tag{1}$$

where $p_0 \in [0,1]$ is the initial probability of dying, or the baseline mortality 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 $u > v$, with u (resp. v) strictly increasing (resp. weakly increasing). 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):[6]

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

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.

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[6] 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 $C_0(z)$ is defined by $(1-p_0+z)u(w-C_0(z))+(p_0-z)v(w-C_0(z))=(1-p_0)u(w)+p_0v(w)$ in which z is the risk reduction. We obviously get $\mathrm{VSL}_0 = C_0'(0)$.

In this model, the VSL increases with an increase in the baseline mortality 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). Notice that the dead-anyway effect can be potentially important in magnitude for large baseline mortality 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 total probability of death has little incentive to limit his spending on 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 mortality 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 mortality 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 mortality 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 Klibanoff et al. (2005)'s model of ambiguity attitude. Formally, and adapting the model above, the decision maker's utility is now written

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

in which $\tilde{p}\ (\equiv p_0 + \tilde{\varepsilon}) \in [0,1]$ 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 $E\tilde{\varepsilon} = 0$. A natural interpretation of this model is that there is a two-stage lottery, first a subjective lottery which determines one's baseline mortality risk $\tilde{p}$, and second an objective lottery which determines whether one is alive or dead. In short, Klibanoff et al. (2005) assume that preferences over these two lotteries are (subjective) expected utility preferences, although permitting a different risk attitude towards each lottery,[7] giving rise the expression of an expected utility of an expected utility.

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[7] Hence, Klibanoff et al. (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, when 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 Klibanoff et al. (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.

The novelty in model (3) compared to model (1) is the introduction of the increasing function ϕ which captures the attitude towards ambiguity. More precisely, the decision-maker has ambiguity averse (seeking) preferences if and only if ϕ is concave (convex), as shown by Klibanoff et al. (2005). In this framework, similar to the usual financial risk aversion which is captured by the concavity of the utility function u, ϕ 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, $\phi(x)=x$. Klibanoff et al. (2005)'s model yields Gilboa and Schmeidler (1989)'s well-known maxmin ambiguity model as a limiting case for infinitely ambiguity averse decision makers ($\alpha\to\infty$).[8] But, in contrast to the Gilboa and Schmeidler's framework, the Klibanoff et al.'s model distinguishes ambiguity (over a set of probability distributions) and ambiguity attitude.

Observe that under a concave ϕ, utility W 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 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):[9]

$$\mathrm{VSL_A}\equiv\frac{\mathrm{dw}}{\mathrm{dp_0}}=\frac{(u(w)-v(w))E\phi'\{(1-\tilde{p})u(w)+\tilde{p}v(w)\}}{E((1-\tilde{p})u'(w)+\tilde{p}v'(w))(\phi'\{(1-\tilde{p})u(w)+\tilde{p}v(w)\})} \tag{4}$$

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.[10] Notice also that without ambiguity aversion (or under expected utility), that is under ϕ' constant, we would get

$$\mathrm{VSL_0}=\frac{u(w)-v(w)}{E((1-\tilde{p})u'(w)+\tilde{p}v'(w))} \tag{5}$$

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

[9] Defining again the willingness to pay $C_1(z)$ for a risk-reduction z by $E\phi\{(1-\tilde{p}+z)u(w-C_1(z))+(\tilde{p}-z)v(w-C_1(z))\}=E\phi\{(1-\tilde{p})u(w)+\tilde{p}v(w)\}$, it is easy to retrieve $\mathrm{VSL_A}=C_1'(0)$.

[10] Alternatively, one could attempt to introduce ambiguity over the risk change (as opposed to over the baseline risk). Consider for instance the willingness to pay $C(z)$ defined by the following equality: $\phi^{-1}\{E\phi\{(1-p_0+\tilde{k}z)u(w-C(z))+(p_0-\tilde{k}z)v(w-C(z))\}\}=(1-p_0)u(w)+p_0v(w)$. Notice that ambiguity (and the expectation operator) is over the random variable $\tilde{k}$. There is thus ambiguity over the risk change $\tilde{k}z$, and not about the baseline mortality risk. In that case, it is easy to see that ambiguity aversion reduces, and not increases, the willingness to pay $C(z)$. However, ambiguity aversion has no effect on the approximated willingness to pay for a small risk change, that is $C'(0)$.

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:

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

Straightforward computations then show that this inequality holds true if and only if $COV((1-\tilde{p})u'(w)+\tilde{p}v'(w), \phi'\{(1-\tilde{p})u(w)+\tilde{p}v(w)\}) \leq 0$. That is, using the well-known covariance rule,[11] if and only ϕ' is decreasing, assuming $u' \geq v'$. Hence, provided death reduces the marginal utility of wealth, ambiguity aversion always reduces the VSL.[12] 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 Klibanoff et al. (2005): a "more concave" ϕ 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 mortality risk $\tilde{p}$ takes a value p_i with a probability q_i, with $\sum_{i=1}^{n} q_i = 1$ (remember also that $E\tilde{p} = \sum_{i=1}^{n} q_i p_i = p_0$). Let us then rewrite the VSL under ambiguity aversion

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

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

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

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 ϕ is concave.

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[11] Assume that $f(p)$ is increasing in p. The covariance rule states that $COV(f(\tilde{p}), g(\tilde{p})) \leq 0$, 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).

[12] 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 immediate to show, using the same demonstration, that ambiguity over probabilities reduces the VSL under $u' \geq v'$. Hence, 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 mortality risk so that the decision maker has the same VSL as in the ambiguous situation. Technically, a new probability $\hat{q}_i$ is associated to each baseline mortality risk p_i, $i = 1,...,n$. 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 mortality risks. Notice also that this weight which affects the perceived increase in the baseline risk depends on individual characteristics (ϕ,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 the same result 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.[13] Along these lines, the effect of ambiguity over baseline risks to *health* (nonfatal risks) would also depend on how health status affects 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 mortality risk they would judge as equivalent to the ambiguous risk they face. We coin it the "utility-equivalent" certain baseline mortality risk. Formally, let us denote $\overline{p}$ this utility-equivalent mortality risk; it is given by the following equation:

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

One may then wonder how $\overline{p}$ compares to the "VSL-equivalent" baseline mortality risk, now denoted $\hat{p} \equiv \hat{E}\tilde{p}$, that we derived in the previous section. After simple manipulations, it is easy to see that

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

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

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[13] 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 (maybe 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-averters, and has precisely more weight under ambiguity aversion.

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

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

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

This inequality is in fact always true under ϕ concave. To see this, 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 λ under ϕ 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 mortality risk is always lower than the VSL-equivalent certain baseline mortality 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 strictly 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 they would have for the certain 191 in a million baseline mortality risk, and even if the mean of the baseline risk is equal to 175.

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 papers about ambiguity over risks to life and health mentioned in the introduction have not elicited 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 $\gamma \in [0,1[$,[14] with no bequest motive, that is $v = 0$. In that case, the VSL is simply equal to $w(1-\gamma)^{-1}(1-p_0)^{-1}$. To

[14] Parameter γ less than 1 guarantees $u > v$.

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 mortality risk. Notice also that the VSL increases nonlinearly with this baseline mortality 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 mortality risk is located.[15] 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 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 α 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, the 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 somehow 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 $p_1=1/2$ (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 α. 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, and 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

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[15] 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 mortality risk is equal to $p_0/(1-p_0)$. The VSL is thus quite sensitive to a change in p_0 only for high values of p_0.

Let us assume now 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

$$\phi^{-1}\{\frac{1}{n}\sum_{i=1}^{n}\phi\{(1-p_i)u(w)+p_i v(w)\}\} \tag{12}$$

The previous analysis assumed that a (infinitesimal) risk change applies uniformly to all p_is. This may be viewed as somehow restrictive, as risk changes might possibly affect *differently* each baseline mortality risk p_i. We call a "differentiated risk change", a change in risk that is different across the p_is. 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. Namely, the prevention measure is only efficient in the worst-case scenario leading to the maximal baseline mortality risk.[16]

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 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_is under ambiguity aversion.

To further study this problem, we denote VSL^i the marginal rate of substitution between wealth and a change in the baseline mortality risk p_i,[17] to get:

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

The quantity $\mathrm{VSL}^{\mathrm{i}}$ 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 $\mathrm{VSL}^{\mathrm{i}}$ 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 $\mathrm{VSL}^{\mathrm{j}}$-$\mathrm{VSL}^{\mathrm{i}}$ has the sign of $\phi'\{(1-p_j)u(w)+p_j v(w)\}-\phi'\{(1-p_i)u(w)+p_i v(w)\}$, 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 on 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 we have only discussed the benefit side of prevention measures. A full examination of how the

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[16] Another example is when an intervention reduces the risk by a constant fraction (e.g., if it reduces exposure to a risk by half).

[17] 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_0s constant in all $p_j, j \neq i$.

decision maker would optimally select the "differentiation" of risk changes must account for the relative cost of these measures.

9. A Self-protection Model

We have studied so far how ambiguity aversion affects the monetary-equivalent value of some prevention measures. The objective of this section is to study how ambiguity aversion affects individual prevention choices. To do so, we need to be more general about how prevention efforts lead to a risk reduction of the baseline mortality risks. We capture this by introducing the function $p_i(e)$, that represents how the baseline mortality risk varies with the prevention effort. We assume that more 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

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

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 assumption and under ambiguity aversion. The first order condition characterizing the optimal e can be written as follows

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

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 ϕ' constant.

In order to compare with the results obtained before, assume 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 $i = 1,...,n$). Then, it is straightforward (using similar manipulations as above including the use of the covariance rule) to prove that ambiguity aversion always increases the prevention effort, under $u' \geq v'$. This result is not a surprise. If an individual who is ambiguity averse does always value more a marginal unit of prevention (implying a higher VSL) than an ambiguity neutral individual, she should also select a higher level of prevention.

However, the result that ambiguity aversion always increases the prevention effort is not general. Indeed, the comparative static analysis depends on the form of $p_i(e)$. To see this, assume for instance 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 $i = 1,...,n$), and assume also that there is no bequest motive $v = 0$. Then, it is easy to show that (15) simply reduces to

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

Consequently, ambiguity aversion has strictly no effect on the prevention effort in this case. Our intuition for this result is that an increase in the prevention effort, although reducing the expected baseline mortality risk, also increases the level of ambiguity faced by the agent. 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 have studied before captures solely an aspect of the relationship between prevention motives and ambiguity aversion. In particular, we have considered a specific model in which the initial situation is ambiguous but the effect of the actions of prevention is not ambiguous (see also the discussion in the footnote 9). It is thus important to keep in mind that ambiguity aversion may 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 Klibanoff et al. (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 Gadjos 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 show that our results extend to this alternative theory of ambiguity.

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

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

in which α 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 of the minimum of expected utility and of the expected utility.

Using this formulation, it is then easy to show that (remember that $\tilde{p} \equiv p_0 + \tilde{\varepsilon}$)

$$\text{VSL}_\text{I} \equiv \frac{dw}{dp_0} = \frac{u(w)-v(w)}{(1-\alpha)(E(1-\tilde{p})u'(w)+\tilde{p}v'(w))+\alpha((1-p_1)u'(w)+p_1v'(w))} \tag{18}$$

which is also equal to

$$\text{VSL}_\text{I} = \frac{u(w)-v(w)}{(1-p^*)u'(w)-p^*v'(w)} \tag{19}$$

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

Most notably, it is then immediate that VSL_{I} increases with the parameter of ambiguity aversion α, 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 mortality risk and the VSL-equivalent baseline mortality risk, unlike in the previous framework based on Klibanoff et al. (2005)’s theory of ambiguity aversion. This observation may suggest a simple way to discriminate empirically between the two theories of ambiguity that we have considered in this paper in the context of risks to life and health.

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):

$$g(1-p_0)u(w)+(1-g(1-p_0))v(w) \tag{20}$$

in which $g(.)$ is usually coined the decision weight function (Quiggin, 1982; Yaari, 1987). When $g(.)$ is linear, we are back to the expected utility model. When $g(.)$ is convex, it can be shown that the decision-maker is averse to any mean-preserving spread under a concave state-independent utility function (Chew et al., 1987). Under these preferences, the VSL equals[18]

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

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.[19] Ambiguity aversion then reduces to a complex property on $g(.)$ (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 the characterization of 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

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[18] See also Bleichrodt and Eeckhoudt (2006). This expression makes it clear the type of conditions such that VSL is higher under RDEU than under expected utility. Assume that $v(.)=0$, then VSL_{RDEU} is higher than VSL_0 if and only if that $g'(p) \geq g(p)/p$, that is $g(p)/p$ increasing in p. This condition is weaker than $g(.)$ convex, and corresponds to the notion of $g(.)$ “star-shaped at 0” defined in Chateauneuf et al. (2004).

[19] 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).

probability 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

$$g(q_2)g(1-p_2)u(w)+(1-g(q_2))g(1-p_1)u(w) \tag{22}$$

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

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

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:

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

which is positive, and then *negative* for some increasing values of ε 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 have an ambiguous effect on the VSL. 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.[20]

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 are delivered to participants in surveys. As shown by Viscusi et al. (1991), the communication of ambiguous risk information may have an effect on partipants' 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

[20] We must add, however, that the classical Pratt (1964)'s concept of comparative risk aversion is not clear-cut under state-dependent preferences (Karni, 1983).

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 however is that what should matter is the additional *welfare* gain associated with the 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.[21]

13. Conclusion

Many mortality risks are ambiguous. The sources of ambiguity are multiple. They may include scientific uncertainty, 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 observed "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.

[21] Interestingly, Camerer et al. (2007), using the technique of fMRI (functional magnetic resonance imaging), show that some 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).

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 subjective beliefs. Following Klibanoff et al. (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

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

is lower than

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

where $\phi_1'\{.\}$ stands for $\phi_1'\{(1-\tilde{p})u'(w)+\tilde{p}v'(w)\}$. But, using (7), notice that we can write

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

and

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

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 ϕ' 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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