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The value of a statistical life under ambiguity aversion

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ABSTRACT

The paper shows that ambiguity aversion increases the value of a statistical life if the marginal utility of an increase in wealth is larger if one is alive rather than dead. Intuitively, ambiguity aversion has a similar effect as an increase in the perceived baseline mortality risk, and thus operates as the "dead anyway" effect. A numerical example suggests, however, that ambiguity aversion cannot justify the substantial "ambiguity premium" apparently embodied in environmental policy-making. The paper also shows that ambiguity aversion decreases the marginal cost of individual self-protection effort but may well decrease its marginal benefit, so that the total effect of ambiguity aversion on self-protection is unclear.

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. Recall 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.

A second example relates to climate change, which is likely to increase worldwide mortality due to heat stress, malnutrition and vector-borne diseases. The World Health Organisation estimates that just a 1 °C increase in global temperature could lead to at least 300,000 annual deaths from climate change [52, 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 [30, p. 198].

How do we react to the uncertainty over the probability of dying from a specific risk? Do we behave as if we *average* the probabilities given by different experts (or different scenarios)? Or do we tend to place excessive weight on the most pessimistic one? The former is consistent with the standard expected utility approach, while the latter may be consistent with an approach that allows for an ambiguity aversion effect.

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Since Ellsberg's [17] seminal paper, experimental work has consistently shown that subjects are not indifferent to ambiguity over probabilities [7]. The development of theories of ambiguity and of ambiguity attitude is more recent. Some influential contributions include Gilboa [21], Segal [48], Schmeidler [47], Gilboa and Schmeidler [22], Klibanoff [35], Epstein and Schneider [18], Ghirardato et al. [20], Klibanoff et al. [36] and Maccheroni et al. [39]. These theories have been mainly applied to financial risks so far.[1] For example, Chen and Epstein [11] 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 presented in Viscusi et al. [64]. In this analysis, survey participants were presented the possibility to live in two areas, A and B, in which there is a risk of nerve disease due to environmental pollution. In the Area A, risks are ambiguous: the risk of disease per million residents could be either 150 cases or 200 cases. A second treatment increased the risk of disease per million residents to either 110 cases or 240 cases (so that the mean risk remained 175 cases). In each treatment, participants were asked what non-ambiguous risk in the Area B they would view as *equivalent* to the ambiguous risk posed in the Area A. Interestingly, survey participants did not simply average baseline risks across the two studies. In treatment 1, mean response was 178; in treatment 2, mean response was 191. Hence, this survey study seems to indicate that participants disliked ambiguity, and disliked greater ambiguity.[3]

These results raise the question of the effect of ambiguity aversion on individuals' monetary-equivalent values in face of a change in ambiguous risks. Suppose that a public prevention program is expected to reduce the risk in Area A; for example by reducing the risk by a certain number of statistical cases in each scenario described by the two studies. What is the individual willingness to pay for this risk-reduction program? And to which extent does the presence of ambiguity aversion affect this willingness to pay? Our first objective in this paper is to study this second question. More precisely, we study the theoretic impact of ambiguity aversion in a standard static value of a statistical life (VSL) model. We mostly consider situations where the baseline risk is ambiguous (i.e., ambiguity may be represented by the different estimated probabilities produced by the two studies), but where the risk reduction is non-ambiguous (i.e., the risk reduction may be represented by a certain and an identical reduction of the two different probabilities). These assumptions are relaxed when we consider differentiated risk changes and a self-protection model.

We mostly consider the recent theory of ambiguity aversion developed by Klibanoff et al. [36] (hereafter KMM), that introduces a simple and an 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 so long as the decision maker's marginal utility of wealth is larger 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 [43]. Namely, the effect of ambiguity aversion on the VSL is similar to that of a perceived increase in the baseline mortality risk within the expected utility model. We also briefly consider alternative theories of ambiguity aversion, and show that similar results may, or may not, obtain. 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 the reduction of ambiguous risks compared with that of 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 [60] 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. As he explains, the 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). The 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. For example,

[1] Some recent exceptions include the theoretical papers by Lange [38] on climate change policy, Chambers and Melkonyan [9] on the trade of toxic products and (d')Albis and Thibault [2] on savings behaviour in face of ambiguous longevity.

[2] Ritov and Baron [46] 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 [45] show, using a survey of Nevada residents, a substantial effect of ambiguity concerning risks from nuclear-waste transport. Shogren [50] reports a survey study about a food-borne illness posing ambiguous risks; see Section 7 for more details.

[3] A related effect is documented in Viscusi [59]. He presents to survey participants conflicting information about an environmental risk, and shows that participants treat the "high risk" information as being more informative. See also Viscusi and Chesson [61].

[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 be extended to state-dependent preferences [40].

[5] Relatedly, Adler [1] discusses what he calls the "de minimis" risk, namely 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 instrumental for defining policy objectives. A recurrent problem is that risk cut-offs are usually extremely low, leading to very high safety standards, without a careful consideration of the economic costs of these standards.

the excess mean risk (e.g. due to dioxin) was overestimated by a factor larger than a thousand of times by US EPA [4]. As Viscusi and Hamilton [62, p. 103] suggest: "[t]hese biases, in effect, institutionalize ambiguity aversion biases". Along similar lines, Sunstein [53] 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 [55] 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 [60], and often a much higher figure is reached in the range of hundreds of millions or even billions dollars [54], as was the case for the Superfund program [62]. In contrast, revealed and stated preferences studies in developed countries in general obtain an individual VSL ranging from \$1 to \$10 million [65]. 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 [56,57]. 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 apparent 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 [53,60]. 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 one use these VSL estimates to compute the social benefits of reducing *ambiguous* risks?

There is little rationale for a positive answer 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 [3,14,60,65]. 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 well account for ambiguity either. Consequently, most VSL estimates do not seem to capture an "ambiguity premium". This may lead to under-estimate the VSL that is 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

Consider a society composed of 100,000 identical individuals, each of whom faces 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 individual tradeoff between a change in wealth and a change in mortality risks.

We now introduce the standard static VSL model [15,31,65,67]. An individual maximizes a (state-dependent) expected utility given by

$$V = (1 - p_0)u(w) + p_0 v(w), \tag{1}$$

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 $u > v$ and $u' \geq v' \geq 0$. Note that the analysis of mortality risks naturally leads one to consider a model with only two states of the world. This greatly simplifies the technical analysis; the generalization to a continuous model of states is by no means immediate [51].

Theoretically, the VSL is defined by the marginal rate of substitution between wealth w and baseline risk p_0. It thus captures this tradeoff just mentioned 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]

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

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.

In this model, the VSL increases with an increase in the baseline risk [67]. 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

[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 $C_0(z)$ for a risk-reduction z is defined by $(1 - p_0 + z)u(w - C_0(z)) + (p_0 - z)v(w - C_0(z)) = (1 - p_0)u(w) + p_0 v(w)$. We obviously get $\mathrm{VSL}_0 = C_0'(0)$.

when the baseline risk increases. This effect has been coined the "dead-anyway" effect [6,27,43]. Some empirical evidence that the VSL increases with the baseline risk may be found in Horowitz and Carson [29] and Persson et al. [41]. 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 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, for example 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 and assumes that each scenario is equally likely, 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's [36] 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 $\tilde{p}\equiv p_0+\tilde{\varepsilon}$ is a positive random variable that represents the ambiguity over the baseline mortality risk, and E denotes the expectation operator over the random variable $\tilde{\varepsilon}$. For the sake of comparison, we will assume throughout that the decision-maker's (subjective) beliefs are such that $E\tilde{\varepsilon}=0$, which allows us to consider a mortality risk of the same magnitude as above. Also, we assume that the realizations of $\tilde{p}$ belong to $[0,1]$. A natural interpretation of this model is that there is a two-stage lottery, the first determining one's baseline mortality risk $\tilde{p}$, and the second determining whether one is alive or dead. In short, KMM [36] assume that preferences over these two lotteries are (subjective) expected utility preferences, although permitting a different risk attitude towards each lottery,[7] 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 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) [36]. In this framework, similar to the usual financial risk aversion which is captured by the concavity of the utility function u, the function ϕ captures the attitude towards ambiguity. Assuming differentiability, $\phi''<0$ thus represents strict ambiguity aversion. There are two important particular cases of this model. First, under $\phi(x)=x$, there is ambiguity neutrality, which is observationally equivalent to expected utility. Second, under $\phi(x)=(1-\exp(-\alpha x))/\alpha$, there is constant ambiguity aversion, which under some conditions yields Gilboa and Schmeidler's [22] 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 KMM's model distinguishes ambiguity (over a set of probability distributions) and ambiguity attitude.

Observe that under a concave ϕ compared to a linear ϕ, the 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 higher under ambiguity aversion than under ambiguity neutrality. However, this result does not permit one to infer the effect of ambiguity for (infinitesimally) small mortality risk changes, as is usually done in the VSL literature.

The natural extension of the VSL under ambiguity and ambiguity aversion is obtained by a total differentiation of (3)[9]:

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

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. Notice also that under ambiguity neutrality (or under expected utility),

[7] Hence, KMM [36] assume a unique subjective belief over the first-stage lottery, but relax the reduction axiom, and thus weight the probabilities nonlinearly [48]. 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 the reduction axiom should apply between both lotteries, so that we are back to expected utility maximization. Second, and alternatively, having a strictly formal interpretation of KMM's [36] theory, both lotteries are different mathematical concepts, and it is possible 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's [26] experimental data.

[8] Assuming $\phi(x)=(1-\exp(-\alpha x))/\alpha$, the ambiguity aversion model is strongly connected to the robust control theory [28,32].

[9] 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 $\mathrm{VSL_A}=C_1'(0)$.

that is under ϕ' constant, we would get

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

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 for all $\tilde{p}$:

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

It is equivalent to say that this last inequality holds if and only if $COV((1-\tilde{p})u'(w) + \tilde{p}v'(w), \phi'\{(1-\tilde{p})u(w) + \tilde{p}v(w)\}) \leq 0$ for all $\tilde{p}$. That is, using the covariance rule,[10] this holds if and only if ϕ' is decreasing, assuming $u' \geq v'$. Hence, provided death reduces the marginal utility of wealth compared to life, ambiguity aversion always reduces the VSL.[11] 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: a "more concave" ϕ always leads to an increase in VSL [58].

5. An intuition based on the dead-anyway effect

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

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

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

$$\hat{q}_i = \frac{q_i \phi'\{(1-p_i)u(w) + p_i v(w)\}}{\sum_{i=1}^{n} q_i \phi'\{(1-p_i)u(w) + p_i v(w))\}} \quad \text{for all} \quad i = 1, \ldots, n, \tag{7}$$

Then, using the covariance rule again for discrete random variables, it is straightforward to show that $\hat{E}\tilde{p}(= \sum_{i=1}^{n} \hat{q}_i p_i) \geq E\tilde{p}$ if and only if ϕ is concave.

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, $i = 1, \ldots, n$. Observe that in the probability $\hat{q}_i$, the probability 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, namely, 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 (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 marginal value of an increment in wealth is larger if one is alive rather than dead. This assumption seems sensible, and is usually accepted without much discussion. Nevertheless, it 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 our result.[12] 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 [63], then our result carries over.

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[10] 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, Kimball [34] for an early reference, and see Gollier [23, p. 95] for a simple proof based on the diffidence theorem.

[11] 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.

[12] 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 negative effect has precisely more weight under ambiguity aversion.

6. Equivalent certain baseline mortality risks

Viscusi et al. [64] asked respondents to state the *certain* baseline risk they would judge as equivalent to the ambiguous risk they face. We will refer to this as the "utility-equivalent" certain baseline risk, and denote it $\bar{p}$; it is implicitly given by the following equation:

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

Obviously under ϕ 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 $\hat{p} \equiv \hat{E}\tilde{p}$. After simple manipulations, it is easy to see that

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

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

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

for all $\tilde{p}$, u and v. This last inequality can be expressed more compactly as

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

The inequality in (11) always holds true when ϕ is concave [66]. Indeed, let $\hat{x}$ be the certainty equivalent of $\tilde{x}$, $\phi\{\hat{x}\}=E\phi\{\tilde{x}\}$, and define the function $g(\lambda)=E\phi\{\lambda\hat{x}+(1-\lambda)\tilde{x}\}$. If ϕ is concave then $g(\lambda)$ is concave in λ, so that $g(\lambda) \geq \lambda g(0)+(1-\lambda)g(1)=g(0)$ for any $\lambda \in [0,1]$. It follows that $g'(0) \geq 0$, 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 again Viscusi et al.'s [64] 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).

7. A numerical illustration

Of the few empirical papers dealing with ambiguity over risks to life, the only study we are aware of that elicits monetary-equivalent values is one mentioned in Shogren [50] about a food-borne pathogen, *Salmonella*. This survey study compares monetary equivalents for risk elimination under non-ambiguous and ambiguous probabilities. Ambiguity occurs because two different probabilities of contracting *Salmonella* were given by two food safety inspectors. Interestingly, "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" [50, p. 125–26].

We now briefly illustrate our theoretic result using some of the figures reported in [50]. 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 $0 \leq \gamma < 1$, and no bequest motive ($v=0$).[13] 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.[14] 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 reported in [50], that the baseline mortality risk is either equal to $p_1=1/666$ or to $p_2=1/2000$. If we assume that these baseline risks are perceived as equally likely, we have $E\tilde{p}=1/1000$. With these probabilities, and with $u(w)=\sqrt{w}$ and wealth equal to \$1 million, 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 behaves 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. This numerical illustration is consistent with a modest effect of ambiguous probabilities [13,50].

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[13] Parameter γ strictly less than 1 insures $u>v$.

[14] 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.

While based on arbitrary functional forms and on arbitrary parameters, this example suggests that the effect of ambiguity aversion is likely to be modest. We believe that this insight should carry over in most "regular" numerical exercises. Indeed, the 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 a modest impact on the VSL because the dead-anyway effect is small for non-extreme baseline risks. Obviously, we cannot exclude that some individuals may judge that their probability of death may be extraordinary high under some scenarios (as might the case for climate change for instance), and also that these individuals have an extreme ambiguity aversion.[15] Nevertheless, since these conditions are somehow extreme, we are tempted to conclude that ambiguity aversion can hardly justify a *systematic* very high implicit cost per life saved, as the one commonly observed for many public environmental programs (e.g., several hundreds of millions dollars per life saved). But clearly more research is needed on this question.

8. Differentiated risk changes

Now suppose that there are n equally likely baseline mortality risks p_i, $i = 1, \ldots, n$, with $p_1 \geq p_2 \geq \ldots \geq p_n$. The decision-maker's utility is then given by

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

The previous analysis assumed that a (infinitesimal) risk change applies uniformly to all p_is (through a reduction of p_0 in $p_i = p_0 + \varepsilon_i,\ i = 1, \ldots, n$). 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_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 is 0 otherwise. In this case, the prevention measure is only efficient in the worst-case scenario leading to a reduction in 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 the baseline mortality risk p_i,[17] to get

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

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 $\mathrm{VSL}^j - \mathrm{VSL}^i$ 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 to the highest baseline mortality risk p_1, rather than a similar risk reduction contingent to any other 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 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 values more a marginal unit of prevention (implying a higher VSL) than an

[15] Consider the following example. 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 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.

[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 $p_j, j \neq i$.

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 reduce mortality risks. We therefore introduce the general function $p_i(e)$, that represents how the baseline mortality risk varies with the prevention effort. We assume that the prevention effort strictly decreases the baseline mortality risk $p_i'(e)<0$, at a decreasing rate $p_i''(e) \geq 0$. Importantly, observe that the effectiveness of the effort of prevention $-p_i'(e)$ is ambiguous in general, as it depends on i.[18]

The objective of the decision maker is to choose the prevention effort e to maximize

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

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 $u'>v'$ and u and v concave. This implies that the second order condition of the program in (14) is satisfied under ambiguity aversion. The first-order condition characterizing the optimal e can be written as follows:

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

The numerator of the left-hand side of equality (15) corresponds to the marginal benefit of prevention while the denominator corresponds to the marginal cost of prevention. Observe that this expression is similar to the VSL expression in (4), except for the quantity $-p_i'(e)$ in the numerator. Using standard comparative statics arguments, 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 for all e.[19]

Let us therefore study the effect of ambiguity aversion on both the denominator and the numerator of the left-hand side of (15). 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 ϕ' decreasing and $u' \geq v'$. This implies that the marginal cost of prevention is always reduced under ambiguity aversion compared to under ambiguity neutrality (by still using the covariance rule, see footnote10). Notice that this holds for any function $p_i(e)$. Nevertheless, the second effect on the numerator capturing the effect of ambiguity aversion on the marginal benefit of prevention is unclear. Indeed, by the same reasoning, it is easy to see that this effect depends on how $p_i(e)$ co-varies with $-p_i'(e)$. As this co-variation depends on the specification of $p_i(e)$, the overall impact of ambiguity on the prevention effort cannot be signed in general.

To illustrate these effects on the marginal cost and on the marginal benefit of self-protection, consider two simple examples. Assume first that the baseline mortality risk is given by an additive form $p_i(e) = p_i - r(e)$ (with $0 \leq r(e) \leq p_i$ for $i = 1, \ldots, n$, and with $r'(e)>0$ and $r''(e) \leq 0$), so that the covariance between $p_i(e)$ and $-p_i'(e)$ (which equals $r'(e)$ and thus does not depend on i) is zero. In other words, the effectiveness of prevention efforts is non-ambiguous in that case and only the first negative effect on the marginal cost of prevention mentioned above is at play. It is straightforward in that case to prove that ambiguity aversion always increases the prevention effort, under $u' \geq v'$.

Alternatively , suppose that the baseline mortality risk is given by the multiplicative form $p_i(e) = 1-\rho_i s(e)$ (with $0 \leq \rho_i \leq 1/s(e)$ for $i = 1, \ldots, n$ and with $s(e)>0$, $s'(e)>0$ and $s''(e)>0$), and assume also that there is no bequest motive $v = 0$. Then, it is easy to show that (15) reduces to

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

in which case, ambiguity aversion has no effect on the prevention effort: the decrease of the marginal cost of prevention due to ambiguity aversion is exactly compensated by the decrease of the marginal benefit. The intuition for this result is as follows. We have seen in Section 5 that an ambiguity averse decision maker pays relatively more attention to high baseline mortality risks – i.e., low ρ_i cases in this example – than an ambiguity neutral decision maker. Yet, since the effectiveness of prevention $-p_i'(e) = \rho_i s'(e)$ is low for high baseline risks, the behavior of an ambiguity averse decision maker is consistent with a perceived decrease in the effectiveness of prevention efforts in this example. This explains that the marginal benefit of prevention may well decrease with ambiguity aversion.

[18] This idea was initially introduced by Shogren [49] who assumed, within an expected utility framework, that a stochastic variable enters directly into the prevention effort function.

[19] In particular, if this inequality condition is satisfied for all e, the left hand side of (15) is larger than 1 when computed at the optimal level of prevention under ambiguity neutrality. That is, the marginal benefit exceeds the marginal cost at this level, and therefore an ambiguity averse individual has an incentive to increase the prevention effort compared to that of the ambiguity neutral individual.

10. An alternative characterization of ambiguity aversion

The above analysis has considered the KMM's [36] theory of ambiguity aversion that introduces a measure of ambiguity aversion and achieves a separation between ambiguity and ambiguity attitude. The recent Gajdos et al.'s [19] theory of ambiguity also shares these fine properties, but is based on another axiomatics. The purpose of this section is to study whether our main result extends to this alternative theory of ambiguity.

Under Gadjos et al.'s [19] theory, the decision-maker's utility can essentially be written as follows:

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

in which α is the parameter of ambiguity aversion (or "imprecision aversion") and p_1 still denotes the highest baseline mortality risk. This framework, suggested by Ellsberg [17, pp. 664–665], thus considers a linear combination between the expected utility and the minimum of expected utility.

Using this formulation, we easily obtain

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

which is also equal to

$$\mathrm{VSL}_i = \frac{u(w)-v(w)}{(1-p^*)u'(w)-p^*v'(w)}, \tag{19}$$

with $p^*=(1-\alpha)E\tilde{p}+\alpha p_1$. Notice 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. 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^*. Moreover, 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's [36] theory of ambiguity aversion. This last observation may suggest a simple way to discriminate empirically between this theory and the KMM's theory in the context of mortality risks.

Finally, one can obtain similar results using another ambiguity theory: the one based on the preferences proposed by Ghirardato et al. [20]. For these preferences, the decision-maker's attitude is essentially represented by a linear combination of the *maximum* and of the minimum of expected utilities. In this case, by a similar reasoning as above, we easily obtain that the VSL is the same as in (19), but with $p^*=(1-\alpha)p_n+\alpha p_1$ where p_n is the lowest of baseline mortality risk. Then, an increase in ambiguity aversion, as represented by an increase in α, also increases VSL under $u' \geq v'$, still due to the "dead anyway" effect.

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 continuous and strictly increasing with $g(0)=0$ and $g(1)=1$; it is usually coined the decision weight function [44,68]. When $g(.)$ is linear, we are back to the expected utility model (1). When $g(.)$ 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 [12]. Under these preferences, the VSL equals[20]

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

Segal [48] builds on RDEU models to explain the Ellsberg paradox, suggesting that an ambiguous lottery may be viewed as a two-stage lottery. He assumes that the decision maker applies the RDEU model to any lottery, but he relaxes the axiom of reduction of compound lotteries between the first-stage and the second-stage lottery.[21] Ambiguity aversion then reduces to a complex property on $g(.)$ [48, Theorem 4.2, p. 185]. Interestingly, Halevy [26] observes that more than one third of subjects in his experiment seem to exhibit a pattern of choices consistent with Segal's preferences.

[20] See also Bleichrodt and Eeckhoudt [5]. It is not difficult to compare the VSL under the RDEU model to that under the expected utility model. Assume for instance that $v(.)=0$, then $\mathrm{VSL}_{\mathrm{RDEU}}$ is higher than VSL_0 if and only if $g'(x) \geq g(x)/x$, that is $g(x)/x$ increasing in x. This condition on the decision weight function is weaker than $g(.)$ convex, and corresponds to the notion of $g(.)$ "star-shaped at 0" defined in [10].

[21] Segal argues 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 [37].

In the rest of this section, we show by an example that ambiguity aversion in this sense 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 respective probability q_1 and q_2) assuming as before $p_1 > p_2$. We also assume that there is no bequest motive, $v = 0$. 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 as

$$\mathrm{VSL}_S \equiv \frac{g(q_2)g'(1-p_2) + (1-g(q_2))g'(1-p_1)}{g(q_2)g(1-p_2) + (1-g(q_2))g(1-p_1)} \times \frac{u(w)}{u'(w)}. \tag{23}$$

If $q_2 = 0.5$, $p_0 = 0.5$, $p_1 = 0.5+\varepsilon$, $p_2 = 0.5-\varepsilon$ and $g(p) = p^2$, the difference between VSL_S and VSL_{RDEU} equals:

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

Note that this is positive for small values of ε, but 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's Theorem 4.2. Hence, this example shows that ambiguity aversion may actually lead to *reduce* the VSL when ambiguity (represented by ε) is large enough.

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 [16] show that financial risk aversion usually has an ambiguous effect on the VSL.[22] In contrast, we have shown that ambiguity aversion increases the VSL. A simple implication of this observation is that effect of ambiguity aversion need not reinforce that of risk aversion [24] 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 are delivered to participants in surveys. The communication of ambiguous risk information may have an effect on participants' responses [64]. 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 effects of risk aversion and that of ambiguity aversion. While risk aversion has long been considered an empirically relevant phenomenon that should be part of the welfare of individuals, the same is not necessarily true for ambiguity aversion. Some theories of ambiguity aversion may lead to time-inconsistent choices, to some conceptual difficulties in beliefs' updating, or 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 argument is that a primary policy 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" [25]. 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 increases individuals' welfare, and that this welfare gain should be somehow reflected in policy-making.[23]

13. Conclusion

Many mortality risks are ambiguous. The sources of ambiguity may be multiple. They may include scientific uncertainty, conflicting expertise, problems of communication and credibility, or lack of information about individual heterogeneous risk-exposure and differences in susceptibility (e.g., genetics). There is a recognized need to better understand the policy implications of ambiguity aversion. In particular, ambiguity aversion may potentially play an important role in the valuation of health and mortality risks changes within benefit–cost analysis.

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?

[22] We notice, however, that the application of the classical Pratt's [42] concept of comparative risk aversion is not clear-cut under state-dependent preferences [33].

[23] Interestingly, using the technique of functional magnetic resonance imaging (fMRI), Camerer et al. show that subjects' brain areas like the amygdala are more active under the ambiguity conditions in their experiment, and notice that the "amygdala has been specifically implicated in processing information related to fear" [8, p. 131].

We urge to obtain better empirical estimates of individuals' ambiguity aversion. Interestingly, our first numerical exercise suggests that the effect of ambiguity aversion should be small. This supports the view that regulatory decisions should perhaps be shaded away from protecting agents from ambiguous risks. 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.

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References

[1] M.D. Adler, Why de minimis? working paper, University of Pennsylvania Law School, 2007.
[2] H. (d')Albis, E. Thibault, Ambiguity aversion and uncertain longevity, working paper, LERNA, Toulouse School of Economics, 2007.
[3] H. Andersson, N. Treich, The value of a statistical life, in: A. De Palma, R. Lindsay, E. Quinet, R. Vickerman (Eds.), The Handbook of Transport Economics, forthcoming, 2009.
[4] R.R. Belzer, The peril and promise of risk assessment, Regulation 47 (1991) 40–49.
[5] H. Bleichrodt, L. Eeckhoudt, Willingness to pay for reductions in health risks when probabilities are distorted, Health Econ. 15 (2006) 211–214.
[6] F. Breyer, S. Felder, Mortality risk and the value of a statistical life: the dead-anyway effect revis(it)ed, Geneva Pap. Risk Ins. Theory 30 (2005) 41–55.
[7] C.F. Camerer, Individual decision making, in: J.H. Kagel, A.E. Roth (Eds.), Handbook of Experimental Economics, Princeton University Press, Princeton, NJ, 1995, pp. 587–703.
[8] C.F. Camerer, M. Bhatt, M. Hsu, Neuroeconomics: illustrated by the study of ambiguity aversion, in: B.S. Frey, A. Slutzer (Eds.), Economics and Psychology: A Promising New Cross-Disciplinary Field, CESifo Seminar Series, The MIT Press, 2007.
[9] R. Chambers, T. Melkonyan, Pareto optimal trade in an uncertain world: GMOs and the Precautionary Principle, Amer. J. Agr. Econ. 89 (2007) 520–532.
[10] A. Chateauneuf, M. Cohen, I. Meilijson, Four notions of mean preserving increase in risk, risk attitudes and applications to the Rank-dependent expected utility model, J. Math. Econ. 40 (2004) 547–571.
[11] Z. Chen, L.G. Epstein, Ambiguity, risk, and asset returns in continuous time, Econometrica 70 (2002) 1403–1443.
[12] S.H. Chew, E. Karni, Z. Safra, Risk-aversion in the theory of expected utility with rank dependent probabilities, J. Econ. Theory 42 (1987) 370–381.
[13] C. Di Mauro, A. Maffioletti, An experimental investigation of the impact of ambiguity on the valuation of self-insurance and self-protection, J. Risk Uncertainty 13 (1996) 53–71.
[14] G. Dionne, P. Lanoie, Public choice about the value of a statistical life: the case of road safety, J. Transp. Econ. Pol. 38 (2004) 247–274.
[15] J. Drèze, L'utilité sociale d'une vie humaine, Rev. Française Rech. Opérationnelle 6 (1962) 93–118.
[16] L. Eeckhoudt, J.K. Hammitt, Does risk aversion increase the value of mortality risk?, J. Environ. Econ. Manage. 47 (2004) 13–29.
[17] D. Ellsberg, Risk ambiguity and the savage axioms, Quart. J. Econ. 75 (1961) 643–669.
[18] L.G. Epstein, M. Schneider, Recursive multi-priors, J. Econ. Theory 113 (2003) 1–31.
[19] T. Gajdos, H. Takashi, J.-M. Tallon, J.-C. Vergnaud, Attitude toward imprecise information, J. Econ. Theory 140 (2008) 23–56.
[20] P. Ghirardato, F. Maccheroni, M. Marinacci, Differentiating ambiguity and ambiguity attitude, J. Econ. Theory 118 (2004) 133–173.
[21] I. Gilboa, Expected utility with purely subjective non-additive probabilities, J. Math. Econ. 16 (1987) 65–88.
[22] I. Gilboa, D. Schmeidler, Maximin expected utility with non-unique prior, J. Math. Econ. 18 (1989) 141–153.
[23] C. Gollier, The Economics of Risk and Time, The MIT Press, 2001.
[24] C. Gollier, Does ambiguity aversion reinforce risk aversion? Applications to portfolio choices and asset pricing, working paper, LERNA, Toulouse School of Economics, 2006.
[25] J.D. Graham, Comparing opportunities to reduce health risks: toxin control, medicine, and injury prevention, National Center for Public Administration Policy Report No. 192, Dallas, 1995.
[26] Y. Halevy, Ellsberg revisited: an experimental study, Econometrica 75 (2007) 503–536.
[27] J.K. Hammitt, N. Treich, Statistical vs. identified lives in benefit–cost analysis, J. Risk Uncertainty 35 (2007) 45–66.
[28] L.P. Hansen, T.J. Sargent, Robustness, Princeton University Press, Princeton, NJ, 2007.
[29] J.K. Horowitz, R.T. Carson, Baseline risk and preference for reductions in risk-to-life, Risk Anal. 13 (1993) 457–462.
[30] Intergovernmental Panel on Climate Change (IPCC), Working Group 3. Economic and Social Dimensions of Climate Change, Cambridge University Press, 1995.
[31] M.W. Jones-Lee, The value of changes in the probability of death or injury, J. Polit. Econ. 99 (1974) 835–849.
[32] N. Ju, J. Miao, Ambiguity, Learning and Asset Returns, working paper, Boston University, 2007.
[33] E. Karni, Risk aversion for state-dependent utility functions: measurement and applications, Int. Econ. Rev. 24 (1983) 637–647.
[34] A.W. Kimball, On dependent tests of significance in the analysis of variance, Ann. Math. Statist. 22 (1951) 600–602.
[35] P. Klibanoff, Characterizing uncertainty aversion through preference for mixtures, Soc. Choice Welfare 18 (2001) 289–301.
[36] P. Klibanoff, M. Marinacci, S. Mukerji, A smooth model of decision making under ambiguity, Econometrica 73 (2005) 1849–1892.
[37] D.M. Kreps, E.L. Porteus, Temporal resolution of uncertainty and dynamic choice theory, Econometrica 46 (1978) 185–200.
[38] A. Lange, Climate change and the irreversibility effect – combining expected utility and maxmin, Environ. Resource Econ. 25 (2003) 417–434.
[39] F. Maccheroni, M. Marinacci, A. Rustichini, Ambiguity aversion, robustness, and the variational representation of preferences, Econometrica 74 (2006) 1447–1498.
[40] R.F. Nau, Uncertainty aversion with second-order utilities and probabilities, Manage. Sci. 52 (2006) 136–145.
[41] U. Persson, A. Norinder, H. Krister, K. Gralén, The value of a statistical life in transport: findings from a new contingent valuation study in Sweden, J. Risk Uncertainty 23 (2001) 121–134.
[42] J.W. Pratt, Risk aversion in the small and in the large, Econometrica 32 (1964) 122–136.
[43] J.W. Pratt, R.J. Zeckhauser, Willingness to pay and the distribution of risk and wealth, J. Polit. Econ. 104 (1996) 747–763.
[44] J. Quiggin, A theory of anticipated utility, J. Econ. Behav. Organ. 3 (1982) 323–343.

[45] M. Riddel, W.D. Shaw, A theoretically-consistent empirical model of non-expected utility: an application to nuclear-waste transport, J. Risk Uncertainty 32 (2006) 131–150.
[46] I. Ritov, J. Baron, Reluctance to vaccinate: omission bias and ambiguity, J. Behav. Dec. Making 3 (1990) 263–277.
[47] D. Schmeidler, Subjective probability and expected utility without additivity, Econometrica 57 (1989) 571–587.
[48] U. Segal, The Ellsberg paradox and risk aversion: an anticipated utility approach, Int. Econ. Rev. 28 (1987) 175–202.
[49] J.F. Shogren, Endogenous risk and protection premiums, Theory Dec. 31 (1991) 241–256.
[50] J.F. Shogren, Economics of diet and health: research challenges, Food Econ. Acta Agr. Scand. C 2 (2005) 117–127.
[51] J.F. Shogren, T.D. Crocker, Risk, self-protection, and ex ante economic value, J. Environ. Econ. Manage. 20 (1991) 1–15.
[52] N.H. Stern, et al., The Economics of Climate Change, Cambridge University Press, 2007.
[53] C.R. Sunstein, Cognition and cost–benefit analysis, in: M.D. Adler, E.A. Posner (Eds.), Cost–Benefit Analysis, Legal, Economic and Philosophical Perspectives, University of Chicago Press, 2000.
[54] C.R. Sunstein, Risk and Reason: Safety Law and the Environment, Cambridge University Press, 2002.
[55] C.R. Sunstein, Laws of Fear: Beyond the Precautionary Principle, Cambridge University Press, 2005.
[56] T.O. Tengs, M.E. Adams, J.S. Pliskin, D. Gelb-Safran, J.E. Siegel, M.C. Weinstein, J.D. Graham, Five-hundred life-saving interventions and their cost-effectiveness, Risk Anal. 15 (1995) 369–390.
[57] T.O. Tengs, J.D. Graham, The opportunity costs of aphazard social investments in life-saving, in: R.H. Hahn (Ed.), Risks, Costs, and Lives Saved, Oxford University Press, New York and Oxford, 1996.
[58] N. Treich, The value of a statistical life under ambiguity aversion, working paper LERNA, Toulouse School of Economics, 2008. ⟨http://www2.toulouse.inra.fr/lerna/⟩.
[59] W.K. Viscusi, Alarmist decisions with divergent risk information, Econ. J. 107 (1997) 1657–1670.
[60] W.K. Viscusi, Rational Risk Policy, Oxford University Press, 1998.
[61] W.K. Viscusi, H. Chesson, Hopes and fears: the conflicting effects of risk ambiguity, Theory Dec. 47 (1999) 157–184.
[62] W.K. Viscusi, J.T. Hamilton, Are risk regulators rational? Evidence from hazardous waste cleanup decisions, Amer. Econ. Rev. 89 (1999) 1010–1027.
[63] W.K. Viscusi, W.N. Evans, Utility functions that depend on health status: estimates and economic implications, Amer. Econ. Rev. 80 (1990) 353–374.
[64] W.K. Viscusi, W.A. Magat, J. Hubert, Communication of ambiguous risk information, Theory Dec. 31 (1991) 159–173.
[65] W.K. Viscusi, J.E. Aldy, The value of a statistical life: a critical review of market estimates throughout the world, J. Risk Uncertainty 27 (2003) 5–76.
[66] R. Watt, A new approximation for the risk premium with large risks, working paper, presented at the EGRIE conference in Cologne, 2008.
[67] M.C. Weinstein, D.S. Shepard, J.S. Pliskin, The economic value of changing mortality probabilities: a decision-theoretic approach, Quart. J. Econ. 94 (1980) 373–396.
[68] M.E. Yaari, The dual theory of choice under risk, Econometrica 55 (1987) 95–115.