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Summary

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Keywords: Non-expected Utility, Self-protection, Self-insurance, Ambiguity Prudence
JEL Classification: D61, D81, D91, G11

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The Impact of Ambiguity Prudence on Insurance and Prevention*

Loïc Berger†

Abstract

Most decisions concerning (self-)insurance and self-protection have to be taken in situations in which a) the effort exerted precedes the moment uncertainty realises, and b) the probabilities of future states of the world are not perfectly known. By integrating these two characteristics in a simple theoretical framework, this paper derives plausible conditions under which ambiguity aversion raises the demand for (self-)insurance and self-protection. In particular, it is shown that in most usual situations where the level of ambiguity does not increase with the level of effort, a simple condition of ambiguity prudence known as decreasing absolute ambiguity aversion (DAAA) is sufficient to give a clear and positive answer to the question: Does ambiguity aversion raise the optimal level of effort?

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1 Introduction

Self-insurance and self-protection (Ehrlich and Becker, 1972) are two well-known and extensively studied risk management tools used to deal with the risk of facing a monetary loss when market insurance is not available. In both situations, a decision maker (DM) has the opportunity to undertake an *effort* to modify the distribution of a given risk. In particular, the self-insurance effort corresponds to the amount of money invested to reduce the size of the loss occurring in the bad state of the world, while the self-protection effort (also called prevention) is the amount invested to reduce the probability of suffering from the loss. Examples of such efforts may be found in many every day life situations as well as in many different economic fields. From the installation of an airbag system in a car, or investments in adaptation[1] efforts to fight global climate change in the case of self-insurance, to the attendance of driving safety lessons, or investments in mitigation[2] efforts in the case of self-protection.

Though these models have received a great deal of attention in the recent literature, it is worth noting that they have, until now, generally been studied only in simple one-period, two-state settings remaining in the expected utility framework. Although these relatively simple monoperiodic models were well adapted to understand the key properties of the self-insurance/self-protection tools in situations of risk, they appear too restrictive to describe a large number of important issues in at least two aspects. First, there are many situations requiring self-insurance or self-protection in real life, in which the decision to make an effort and the realization of uncertainty do not take place at the same time (consider for instance the examples above). A long period of time may pass between these two events, leading to the necessity of taking intertemporal considerations into account and building multi-period models. The second limitation is that most of the models studied in the literature remain in the expected utility framework, and are therefore unable to deal with other kinds of uncertainty besides *risk*[3]. In many real-life problems however,

[1] "Adaptation is the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate harm or exploit beneficial opportunities" (IPCC, 2014a).

[2] "Mitigation is a human intervention to reduce the sources or enhance the sinks of greenhouse gases"(IPCC, 2014b).

[3] The probability distributions are therefore assumed to be known with certainty. In particular, those models implicitly assume the absence of any kind of ambiguity, or equivalently, assume that agents are ambiguity-neutral (and therefore behave as subjective expected utility maximizers in the sense of Savage (1954)). Notably exceptions to this are the recent papers by Snow (2011) and

the nature of the uncertainty considered cannot be limited to risk since the probabilities associated with the realisation of uncertain events cannot always be objectively known. In these kinds of situation, ambiguity plays a central role, and the attitude agents generally manifest towards this additional source of uncertainty needs to be taken into account. The subjective expected utility theory that assumes ambiguity neutrality is therefore inconsistent in this context. Indeed, as first shown by Ellsberg (1961) and later confirmed by a number of experimental studies[4], the uncertainty on the probabilities of a random event (called ambiguity) often leads the decision maker to violate the reduction of compound lotteries axiom in the sense that it makes him over-evaluate less desirable outcomes. It is therefore important to take this individual behavior (called ambiguity aversion) into account when considering problems in the presence of ambiguity. As an additional example, consider the following case. A young man faces the risk of developing heart disease when he is older, but he can choose whether or not to practice sport in his youth as a preventive measure. Sport is costly, but it can either reduce the probability of heart disease with which a potentially important fixed loss is associated (self-protection), or it can reduce the severity of a disease that develops with a fixed probability (self-insurance)[5]. While it is clear that many years may separate the moment at which the effort decision is taken and the moment at which the uncertainty is realised, an additional difficulty, in such a situation, is that at the time the decision is taken of doing sport on a regular basis or not, the probability of developing a heart disease at old age is unknown[6].

In this paper, I present models of self-insurance and self-protection that are able to overcome the above-mentioned limitations. Each model takes the form of a simple two-period model incorporating the theory Klibanoff, Marinacci, and Mukerji (2005, 2009) developed to deal with ambiguity. The timing of the decision process is simple: in the first period, a DM chooses the level of effort he wants to exert in order to affect either the probability of being in a state in which ambiguity is concentrated in the second period, or to affect the level of wealth in this ambiguous state. Using this setting, I derive the conditions under which ambiguity aversion raises the

Alary, Gollier, and Treich (2013).

[4]See Einhorn and Hogarth (1986), Viscusi and Chesson (1999), and Ho et al. (2002) among others.

[5]Imagine for example that doing sport enables to lower recovery costs, thanks to a better physical condition.

[6]Depending on the value of some parameters such as the blood pressure, cholesterol, etc. different institutes will estimate this probability very differently, as is illustrated in Gilboa and Marinacci (2011).

demand for insurance, self-insurance and self-protection. In particular, I show that when the effort is undertaken during the first period, ambiguity aversion tends to have a positive impact on the demand for (self-)insurance and self-protection. However, as for the study of risk attitude in which risk aversion alone is not sufficient to guarantee a higher level of prevention (since *risk* prudence is also needed), I show that the extra condition of ambiguity prudence attitude is also needed to observe this positive impact. Contrary to the conflicting results obtained in the one-period settings (Eeckhoudt and Gollier, 2005), the close relationship that is achieved between prudence and prevention in the two-period setting (Menegatti, 2009) is then re-established in the presence of ambiguity.

This paper is therefore both an extension of the research on self-insurance and self-protection under ambiguity initiated by Snow (2011) and Alary, Gollier, and Treich (2013) in the sense that it goes from the study of the one- to the two-period problem, but also of Menegatti (2009) as it allows for non neutral ambiguity attitudes. Except from the fact that the results concerning self-insurance under ambiguity are shown to be easily extended to the two-period case, the particular interest of this approach is that it enables to treat the most plausible situations in which the effort of self-protection does not go together with an increase in the degree of ambiguity (think for example to the security, climate change and health examples). In that sense and contrarily to the results obtained in Alary, Gollier, and Treich (2013)[7], this paper enables to give, for most usual situations, a clear answer to the question: *Does ambiguity aversion raise the optimal level of effort?*

The remainder of this paper is organized as follows. In Section 2, I introduce the simple two-period model under ambiguity by studying the problem of full insurance. Then in succession, I analyze the willingness to pay (Section 3) and the optimal effort (Section 4) for self-insurance and self-protection. Section 5 concludes the paper.

2 Full Insurance in the Two-Period Model

The model involves ambiguity: probabilities of the second-period final wealth are not objectively known, instead they consist of a set of probabilities, depending

[7] These authors themselves recognize that the results they obtain for self-protection concern only a restricted, rather implausible, range of situations by noting that "in many situations, it appears more natural that self-protection would reduce both risk and ambiguity".

on an external parameter θ for which the decision maker (DM) has prior beliefs[8]. Ambiguity may therefore be interpreted as a multi-stage lottery: a first lottery determines the value of parameter θ, and a second one determines the size of second-period wealth. The second-period wealth distribution $\tilde{w}_2(\theta)$ is represented by the vector $[w_{2,1}, w_{2,2}, ..., w_{2,n}; p_1(\theta), p_2(\theta), ..., p_n(\theta)]$ with $w_{2,1} < w_{2,2} < \cdots < w_{2,n}$.
In the time-separable model, the intertemporal welfare under Klibanoff, Marinacci, and Mukerji (2005, 2009) (KMM) representation is as follows:

$$u(w_1) + \beta\phi^{-1}\left\{\mathrm{E}_\theta\phi\left\{\mathrm{E}u(\tilde{w}_2(\tilde{\theta}))\right\}\right\}, \tag{1}$$

where w_i is the exogenous wealth in the beginning of period $i = 1, 2$, u represents the period vNM utility functions, $\beta \in [0, 1]$ is the discount factor[9], ϕ represents attitude towards ambiguity, E_θ is the expectation operator taken over the distribution of θ, conditional on all information available during the first period, and E is the expectation operator taken over w_2 conditional on θ. The function ϕ is assumed to be three times differentiable, increasing, and concave under ambiguity aversion, so that the ϕ-certainty equivalent in equation (1) is lower in that case than when the individual is ambiguity neutral characterized by a linear function ϕ[10]:

$$\phi^{-1}\left\{\mathrm{E}_\theta\phi\left\{\mathrm{E}u(\tilde{w}_2(\tilde{\theta}))\right\}\right\} \leq \mathrm{E}_\theta\mathrm{E}u(\tilde{w}_2(\tilde{\theta})) = \mathrm{E}u(\tilde{w}_2) \tag{2}$$

In that sense, an ambiguity averse DM dislikes any mean-preserving spread in the space of conditional second period expected utilities.
The right hand side of expression (2) corresponds to the second period welfare obtained by an ambiguity neutral individual who evaluates his welfare by considering the risky second period wealth $\tilde{w}_2$: $[w_{2,1}, w_{2,2}, ..., w_{2,n}; \bar{p}_1, \bar{p}_2, ..., \bar{p}_n]$ with the mean state probabilities $\bar{p}_s = \mathrm{E}_\theta p_s(\tilde{\theta})$, $\forall s = 1, ..., n$. In that sense, an ambiguity neutral individual is nothing but a Savagian expected utility agent.

As for the single period model, the study of willingness to pay (WTP) P for risk

[8] Imagine that parameter θ can take values $\theta_1, \theta_2, ..., \theta_m$ with probabilities $[q_1, q_2, ..., q_m]$, such that the expectation with respect to the parametric uncertainty is written $\mathrm{E}_\theta g(\tilde{\theta}) = \sum_{j=1}^{m} q_j g(\theta_j)$.

[9] In what follows, I assume that $\beta = 1$, an assumption that has no impact on the results obtained.

[10] Notice that for simplicity, I assume that ϕ is only defined for non-negative values. Any value inside the second bracket must therefore be non-negative, which should not be a problem since any positive affine transformation of u represents the same preferences over risky situations. KMM consider for example the unique continuous, strictly increasing function u with $u(0) = 0$ and $u(1) = 1$ that represents any given preferences.

elimination under ambiguity is straightforward[11]. In this case, it corresponds to the amount an individual is ready to pay in period 1 to escape the uncertainty in period 2, and is defined as follows:

$$u(w_1 - P) + u(\mathrm{E}\tilde{w}_2) = u(w_1) + \phi^{-1}\left\{\mathrm{E}_\theta \phi\left\{\mathrm{E}u(\tilde{w}_2(\tilde{\theta}))\right\}\right\}.$$

If the individual were ambiguity neutral, he would be ready to pay P_0 defined by $u(w_1 - P_0) + u(\mathrm{E}\tilde{w}_2) = u(w_1) + \mathrm{E}u(\tilde{w}_2)$ to eliminate the same risk. Using inequality (2), we can then see that P is always higher than P_0 under ambiguity aversion in the two-period model. As in the single period model, ambiguity averse individuals are therefore ready to pay a higher premium for risk elimination, since the elimination of the risk automatically eliminates the ambiguity attached to this risk. This extra premium is the two-period version of the *ambiguity premium*[12].

3 Willingness to Pay under Ambiguity

Building on Alary, Gollier, and Treich (2013) (AGT hereafter), I now re-examine the willingness to pay (WTP) for infinitesimal insurance or protection in the context of a two-period model. It is assumed that ambiguity is concentrated on a state i. In this case, the ambiguous probability to be in state i is: $p_i(\theta)$, while the probability to be in any other state $s \neq i$ is given by

$$p_s(\theta) = (1 - p_i(\theta))\pi_s,$$

where π_s is the *unambiguous* probability of being in state s[13] conditional on the information that the state is not i. Observe that if there are only two states of nature, this structure reduces to the case with ambiguous probabilities $p(\theta)$ and $1 - p(\theta)$. From now on, I also assume, without loss of generality, that θ may be ranked in such a way that p_i is increasing in θ.

[11]Note that in the single period model studied by Alary, Gollier, and Treich (2013), this willingness to pay P is what Berger (2011) or Maccheroni et al. (2013) call the *uncertainty premium*, which is by definition superior to Pratt's risk premium under ambiguity aversion.

[12]Berger (2011) defines the uncertainty premium as the combination of both the risk and the ambiguity premia.

[13]An implicit assumption is that $\sum_{s\neq i} \pi_s = 1$.

3.1 Self-insurance

Self-insurance in a two-period world is a risk management tool thanks to which an individual has the opportunity to exert an effort today to reduce a cost in a specific state i tomorrow. By letting $P(\epsilon)$ denote the willingness to furnish this effort to increase marginally the wealth in state i and such that the level of welfare is not altered, we have:

$$u(w_1 - P(\epsilon)) + \phi^{-1}\left\{\mathrm{E}_\theta \phi \left\{ p_i(\tilde{\theta}) u(w_{2,i} + \epsilon) + [1 - p_i(\tilde{\theta})] \sum_{s \neq i} \pi_s u(w_{2,s}) \right\}\right\} = u(w_1) + \phi^{-1}\left\{\mathrm{E}_\theta \phi \left\{ \mathrm{E} u(\tilde{w}_2(\tilde{\theta}))\right\}\right\}.$$

Totally differentiating this equation with respect to ϵ and evaluating it at $\epsilon = 0$ leads to

$$P'(0) = \frac{\mathrm{E}_\theta \phi' \left\{\mathrm{E}u(\tilde{w}_2(\tilde{\theta}))\right\} \left[p_i(\tilde{\theta}) u'(w_{2,i})\right]}{\phi'\left\{\phi^{-1}\left\{\mathrm{E}_\theta \phi \left\{\mathrm{E}u(\tilde{w}_2(\tilde{\theta}))\right\}\right\}\right\} u'(w_1)}, \tag{3}$$

and the marginal WTP for self-insurance of an ambiguity neutral individual ($\phi' \equiv$ constant) is:

$$P'_N(0) = \frac{u'(w_{2,i}) \mathrm{E}_\theta p_i(\tilde{\theta})}{u'(w_1)}. \tag{4}$$

An ambiguity averse individual has thus a higher marginal WTP to insure state i if $P'(0) > P'_N(0)$. To compare equations (3) and (4) in the most common case of non increasing ambiguity aversion, I use the following lemma and its corollary:

Lemma 1 (Berger (2014))**.** *Let ϕ be a three times differentiable function reflecting ambiguity aversion. If ϕ exhibits DAAA (Decreasing Absolute Ambiguity Aversion) then* $\mathrm{E}\phi'\{\tilde{x}\} > \phi'\left\{\phi^{-1}\left\{\mathrm{E}\phi\{\tilde{x}\}\right\}\right\}$.

Lemma 1. *If ϕ exhibits CAAA (Constant Absolute Ambiguity Aversion), then* $\mathrm{E}\phi'\{\tilde{x}\} = \phi'\left\{\phi^{-1}\left\{\mathrm{E}\phi\{\tilde{x}\}\right\}\right\}$.

Non increasing absolute ambiguity aversion refers to the notion of ambiguity prudence attitude. This characteristic, which is stronger than requiring $\phi''' > 0$[14], has been shown to be sufficient for ambiguity prudence if ambiguity is concentrated on a particular state i and the agent is risk prudent ($u''' > 0$) (Berger, 2014).

[14]Note that ϕ being DAAA implies $\phi''' > 0$. The difference between the standard *risk* and *ambiguity* prudence conditions comes from the fact that the intertemporal utility (1) is evaluated using a ϕ-certainty equivalent rather than a simple ϕ-valuation.

Ambiguity aversion therefore raises the marginal WTP for insurance in state i if $\text{cov}_\theta(\phi'\{\text{E}u(\tilde{w}_2(\tilde{\theta})\}, p_i(\tilde{\theta})) > 0$ and the individual has an ambiguity prudent attitude. Since p_i is assumed to be increasing in θ, by the covariance rule, and because ϕ' is decreasing under ambiguity aversion, we only need $Eu(\tilde{w}_2(\theta))$ to be decreasing in θ. Decomposing this expression enables us to see that the condition needed is similar to the one in AGT:

$$\text{E}u(\tilde{w}_2(\theta)) = -p_i(\theta)\left[\sum_{s\neq i} u(w_{2,s}) - u(w_{2,i})\right] + \sum_{s\neq i} u(w_{2,s})$$

and $\text{E}u(\tilde{w}_2(\theta))$ is therefore decreasing in θ if ψ defined as the certainty equivalent of second period wealth conditional on the state not being i: $\sum_{s\neq i} \pi_s u(w_{2,s}) = u(\psi)$, is higher than second period wealth in state i: $w_{2,i}$. This leads to the following proposition:

Proposition 1. *In the two-period model of self-insurance in which ambiguity is concentrated on the insured state i, ambiguity aversion raises the marginal WTP to self-insure state i if the individual manifests DAAA and second period wealth in state i is smaller than the second period certainty equivalent ψ.*

The insight this result provides is analogous to the one resulting from the study of willingness to pay for an increase in second period wealth in a Kreps and Porteus (1978)/Selden (1978) model. When the second period wealth in state i is considered as *unfavorable* in the sense that the utility obtained in that state is smaller than his expected utility in the others states, raising $w_{2,i}$ has a positive impact on the the conditional second period expected utilities $\text{E}u(\tilde{w}_2(\theta))$, which is valuable for any individual with $\phi' > 0$. However, this raise in $w_{2,i}$ comes with a cost: an effort that has to be furnished in advance (period 1). In the Kreps-Porteus/Selden model, we know that risk aversion raises the marginal WTP for an increase in second period wealth, provided that the individual is prudent. This condition is only satisfied in that context if the individual manifests decreasing absolute risk aversion (DARA). Given the similarity between Kreps-Porteus/Selden and KMM models, it is therefore not surprising that ambiguity aversion is no more sufficient in guaranteeing that the marginal WTP to self-insure state i increases. An additional condition analogous to prudence is needed. Non increasing absolute ambiguity aversion is this extra condition in the presence of ambiguity

3.2 Self-protection

Another tool that may be used to deal with the presence of uncertainty in the second period is self-protection: an individual has the opportunity to undertake an effort today, in order to alter the probability of a specific state i tomorrow. In this subsection, I examine the effect of ambiguity aversion on the marginal willingness to furnish a self-protection effort in the context of a two-period model.

Proceeding as before, I denote by $P(\epsilon)$ the WTP today for a reduction ϵ in the probability of state i tomorrow, such that the intertemporal level of welfare is not modified. Furthermore, following AGT, I assume that the degree of ambiguityis not altered by the change of p_i: p_i is equally affected for any value of θ, and the distribution of second period wealth conditional on the state not being i remains identical. Mathematically, $P(\epsilon)$ is defined as follows:

$$u(w_1 - P(\epsilon)) + \phi^{-1}\left\{\mathrm{E}_\theta\phi\left\{\left[p_i(\tilde{\theta}) - \epsilon\right]u(w_{2,i}) + \left[1 - p_i(\tilde{\theta}) + \epsilon\right]\sum_{s\neq i}\pi_s u(w_{2,s})\right\}\right\}$$
$$= u(w_1) + \phi^{-1}\left\{\mathrm{E}_\theta\phi\left\{\mathrm{E}u(\tilde{w}_2(\tilde{\theta}))\right\}\right\}.$$

Totally differentiating this expression with respect to ϵ and evaluating it at $\epsilon = 0$ yields:

$$P'(0) = \frac{\left[\sum_{s\neq i} u(w_{2,s}) - u(w_{2,i})\right]\mathrm{E}_\theta\phi'\left\{\mathrm{E}u(\tilde{w}_2(\tilde{\theta}))\right\}}{\phi'\left\{\phi^{-1}\left\{\mathrm{E}_\theta\phi\left\{\mathrm{E}u(\tilde{w}_2(\tilde{\theta}))\right\}\right\}\right\}u'(w_1)}. \tag{5}$$

Assuming again that the second period wealth in state i: $w_{2,i}$ is smaller than the certainty equivalent ψ defined above (i.e that self-protection aims to reduce the probability of an *unfavorable* state) so that the marginal WTP is positive, it may be shown that the marginal WTP to self-protect state i is higher under ambiguity aversion if:

$$\mathrm{E}_\theta\phi'\left\{\mathrm{E}u(\tilde{w}_2(\tilde{\theta}))\right\} > \phi'\left\{\phi^{-1}\left\{\mathrm{E}_\theta\phi\left\{\mathrm{E}u(\tilde{w}_2(\tilde{\theta}))\right\}\right\}\right\}. \tag{6}$$

According to Lemma 1, this will be the case if the individual exhibits DAAA, while nder CAAA, the marginal WTP for self-protection in state i remains the same under ambiguity aversion. Alternatively note also that if $w_{2,i} > \psi$ (i.e if the state to self-protect is a favorable state and the marginal WTP is negative) results are reversed. These results prove the following proposition and its corollary.

Proposition 2. *In the two-period model of self-protection in which ambiguity is concentrated on state i, ambiguity aversion raises (reduces) the marginal WTP to* *self-protect state i under DAAA (IAAA) if second period wealth in state i is smaller than the second period certainty equivalent ψ, and reduces (raises) it otherwise.*

Lemma 2. *In the two-period model of self-protection in which ambiguity is concentrated on state i, ambiguity aversion does not modify the marginal WTP to self-protect state i under CAAA.*

These results are different from the single period model, in which under DARA, ambiguity aversion *reduces* the marginal WTP to self-protect state i if wealth in state i is smaller than the precautionary equivalent wealth level conditional on the state not being i (Proposition 3 in AGT).
The intuition here is similar that made before. As the effect of self-protection on the probability of state i is identical for any value of θ, and since the distribution of other states conditional on $s \neq i$ is not modified, raising p_i has a positive and equal impact on conditional second period expected utility $\mathrm{E}u(\tilde{w}_2(\theta))$ for all values of θ. Due to the introduction of ambiguity aversion, the cost of this increase is paid in the first period so that the extra condition of DAAA is needed to observe a raise in the marginal WTP to self-protect state i.

4 Optimal Effort under Ambiguity

In this section, I examine the impact of ambiguity aversion on the optimal insurance and protection in favor of state i in a two-period model. The general form of the decision maker's problem is given by:

$$\max_{e} u(w_1 - e) + \phi^{-1}\left\{\mathrm{E}_\theta \phi\left\{U(e, \tilde{\theta})\right\}\right\}, \tag{7}$$

where $U(e,\theta) = p_i(e,\theta)u(w_{2,i}(e)) + [1 - p_i(e,\theta)]\sum_{s\neq i}\pi_s u(w_{2,s})$ is the second period expected utility, conditional on the parameter θ. Notations remain as before[15] and e represents the level of effort needed to self-insure or self-protect state i. Problem (7) is a problem of self-insurance when $p_i(e,\theta) = p_i(\theta)$ for all levels of effort e, and a problem of self-protection when $w_{2,i}(e) = w_{2,i}$ for all e. I assume that $p_i(e,\theta)$ and $w_{2,i}(e)$ are differentiable in e and that when state i is *unfavorable*, $p_{ie}(e,\theta) \equiv \frac{\partial p_i(e,\theta)}{\partial e} \leq 0$ for all θ, and that $\frac{\partial w_{2,i}(e)}{\partial e} \geq 0$. Notice that under KMM specification, the concavity of u and ϕ does not guarantee that the maximization problem (7) is convex, so additional assumptions are needed for the programme's solution to be unique. These conditions are summarized in the following proposition.

[15]Remember that β is fixed to unity for simplicity and without altering the final result.

Proposition 3. *The maximization programme of a two-period self-insurance or self-protection problem under ambiguity as described by* (7) *is convex if:*

- *function* ϕ *has a concave absolute ambiguity tolerance:* $-\phi'(U)/\phi''(U)$ *is concave in* U*,*

and

- $w_{2,i}(e)$ *is concave in* e *in the self-insurance case:* $\partial^2 w_{2,i}(e)/\partial e^2 \leq 0$*, or*
- $p_i(e,\theta)$ *is convex in* e *in the self-protection case:* $\partial^2 p_i(e,\theta)/\partial e^2 \geq 0$ *for all* θ*.*

Proof. Relegated to the Appendix. □

In line with the risk theory literature, concave absolute ambiguity tolerance is a property verified by the most widely-used specifications in the literature. In particular, it is satisfied by the families of constant relative ambiguity aversion (CRAA): logarithmic and power functions, of constant absolute ambiguity aversion (CAAA): exponential functions, and of quadratic functions.

In the special case of ambiguity neutrality, problem (7) becomes a simple two-period problem in the expected utility framework. It consists of finding the level of effort e that maximizes:

$$u(w_1 - e) + \mathrm{E}_\theta U(e, \tilde{\theta}).$$

The optimal level of effort e^* chosen by an ambiguity averse individual is the solution of the first-order condition (FOC):

$$-u'(w_1 - e^*) + \mathrm{E}_\theta U_e(e^*, \tilde{\theta}) = 0, \tag{8}$$

where $U_e(e,\theta) = \partial U(e,\theta)/\partial e$. The first term of this expression represents the marginal cost of effort and the second represents the marginal benefits of self-protection or of self-insurance.

Ambiguity aversion therefore raises the optimal level of effort if the FOC of problem (7) evaluated at e^* is positive. This is the case if:

$$\frac{\mathrm{E}_\theta \left[\phi'\{U(e^*,\tilde{\theta})\}U_e(e^*,\tilde{\theta})\right]}{\phi'\left\{\phi^{-1}\left\{\mathrm{E}_\theta \phi\{U(e^*,\tilde{\theta})\right\}\right\}} \geq \mathrm{E}_\theta U_e(e^*,\tilde{\theta}). \tag{9}$$

The interpretation of this condition is simple: as ambiguity only affects variables during the second period, the marginal cost of effort, which takes place in the first

period, is unaffected and the condition indicates that the marginal benefit of protection or insurance must be higher under ambiguity aversion.
Using Lemma 1 and its corollary, we then see that under CAAA, condition (9) is equivalent to:

$$\mathrm{cov}_\theta\left(\phi'\{U(e^*,\tilde{\theta})\}, U_e(e^*,\tilde{\theta})\right) \geq 0. \tag{10}$$

Moreover, condition (9) is always satisfied under DAAA if condition (10) holds. As ϕ' is decreasing under ambiguity aversion, using the covariance rule, the condition therefore becomes:

Proposition 4. *Ambiguity aversion raises the optimal level of effort in a two-period model as the one described by* (7) *if* $U(e^*,\theta)$ *and* $U_e(e^*,\theta)$ *are anti-comonotonic and if the individual manifests DAAA, where* e^* *is defined by* (8).

4.1 Self-insurance

I now investigate the conditions under which this proposition holds in the case of self-insurance. In this case, we must remember that the individual has the opportunity to make an effort e in the first-period to increase his wealth to $w_{2,i}(e)$ in the insurable state i in the second period. The conditional second period expected utility in the case of self-insurance is therefore given by:

$$U(e,\theta) = p_i(\theta)u(w_{2,i}(e)) + [1-p_i(\theta)]\sum_{s\neq i}\pi_s u(w_{2,s}).$$

Since p_i is assumed to be increasing in θ, it is clear that $U(e^*,\theta)$ decreases with θ if $w_{2,i}(e^*) < \psi$, and increases with θ otherwise, while $U_e(e^*,\theta) = p_i(\theta)u'(w_{2,i}(e^*))\frac{\partial w_{2,i}(e^*)}{\partial e}$ is increasing in θ. Combining theses results with condition (9) and using Lemma 1 and its corollary proves the following proposition:

Proposition 5. *In a two-period model of self-insurance of a state i in which ambiguity is concentrated, ambiguity aversion raises the optimal level of self-insurance under DAAA if the second period wealth in state i is smaller than the second period certainty equivalent ψ.*

Note that when $w_{2,i}(e^*) > \psi$, no general conclusion may be drawn. In this case, DAAA may increase or decrease the optimal level of effort.

Lemma 3. *In a two-period model of self-insurance of a state i in which ambiguity is concentrated, ambiguity aversion raises the optimal level of self-insurance under*

CAAA if the second period wealth in state i is smaller than the second period certainty equivalent ψ, and decreases it otherwise.

Example This result extends to a two period framework the results obtained by Snow (2011) in the particular case of a world with two states: a loss and a no-loss state. Under this assumption, if an insurable loss L occurs, the second period wealth is $w_{2,i}(e^*) = w_2 - L(e^*)$, and is $\psi = w_2$ in the no-loss state. Snow's (2011) results showing that ambiguity aversion increases the optimal level of self-insurance are then easily extended to a two-period world if the individual manifests CAAA or DAAA. Finally, if the loss function has the particular form: $L(e) = L - ke$, it is also possible to interpret the results in the context of a standard coinsurance problem where the premium e is paid in first period and for each dollar of which the insured agent receives an indemnity k if the loss occurs. In this case, ambiguity aversion raises the insurance coverage rate if the individual manifests non increasing ambiguity aversion. This result is the two-period version of Corollary 1 in Alary, Gollier, and Treich (2013) and is synthesized in the following corollary:

Lemma 4. *In the standard coinsurance problem with two states in which the insurance premium is paid in first period and uncertainty is realized in second period, ambiguity aversion raises the insurance coverage rate if the individual exhibits DAAA.*

4.2 Self-protection

I now consider the problem of self-protection: the effect of effort is to reduce the probability $p_i(e, \theta)$ of an unfavourable state i in which ambiguity is concentrated. Conditional second period expected utility takes the form:

$$U(e, \theta) = p_i(e, \theta)u(w_{2,i}) + [1 - p_i(e, \theta)] \sum_{s \neq i} \pi_s u(w_{2,s}).$$

As before, and without loss of generality, I assume that $p_i(e^*, \theta)$ is increasing in θ so that $U(e^*, \theta)$ is a decreasing function of θ when state i is unfavourable. From Proposition 4, a sufficient condition to observe a higher level of effort under CAAA or DAAA than under ambiguity neutrality in the self-protection model, therefore becomes that the marginal benefit of effort $U_e(e^*, \theta) = -p_{ie}(e^*, \theta) \left[\sum_{s \neq i} \pi_s u(w_{2,s}) - u(w_{2,i})\right]$ is increasing in θ. The key element is how $-p_{ie}(e^*, \theta)$ evolves with θ, or alternatively how the degree of ambiguity is affected by a change in the level of effortIf the degree of ambiguity is not altered by a change in the level of effort, as it was the case in the section studying the willingness to pay, $p_{ie}(e^*, \theta)$ is independent of θ and the covariance in (10) is equal to zero. In this case, an individual manifesting strictly DAAA will always choose a higher level of self-protection under ambiguity aversion, while an individual manifesting CAAA will self-protect in exactly the same way as an ambiguity neutral agent. If on the contrary, the degree of ambiguity decreases with the level of effort exerted as it seems natural in many situations, $p_{ie}(e^*, \theta)$ is decreasing in θ so that there exists an additional incentive for an ambiguity averse decision maker to raise self-protection. It is therefore clear that in this situation, non increasing absolute ambiguity aversion raises the optimal level of effort. Finally, in the more implausible case where effort increases the level of ambiguity as in AGT, $p_{ie}(e^*, \theta)$ is increasing in θ and the ambiguity prudence attitude effect is not anymore sufficient to raise optimal self-protection. The following proposition and its corollary summarize theses results:

Proposition 6. *In the two-period problem of self-protection of an unfavourable state i in which ambiguity is concentrated, DAAA is sufficient to raise the optimal self-protection effort under ambiguity aversion if effort decreases the degree of ambiguity of state i.*

Lemma 5. *In the two-period problem of self-protection of an unfavourable state i in which ambiguity is concentrated, an agent manifesting DAAA (resp. CAAA) chooses a higher (similar) level of self-protection than (as) an ambiguity neutral agent, if effort does not affect the ambiguity of state i.*

To illustrate what precedes, consider the following examples.

Examples Imagine there are only two states of the world: a loss and a no-loss state in which second period wealth is respectively $w_2 - L$ with conditional probability $p(e, \theta)$, or w_2 with probability $1 - p(e, \theta)$. Consider two particular forms of loss probability functions that are both linear in the ambiguity parameter θ: $p^1(e, \theta) = p(e) + \theta$, and $p^2(e, \theta) = \theta p(e)$.
In the additive case, $U_e(e^*, \theta) = -p'(e^*)\big[u(w_2) - u(w_2 - L)\big]$ so that an increase in θ has no effect on $U_e(e^*, \theta)$. The level of self-protection is therefore exactly the same for any individual manifesting constant ambiguity attitude[16]. In particular, an ambiguity neutral individual and a maxmin expected utility maximizer à la Gilboa

[16]Remember that according to Klibanoff, Marinacci, and Mukerji (2005), constant ambiguity attitude is characterized either by linear or exponential function ϕ.

and Schmeidler (1989) both choose to self-protect precisely the same way. If the individual exhibits DAAA, he will always choose a higher level of protection under ambiguity aversion.

Imagine now that the degree of ambiguity is made smaller when the effort increases in the neighbourhood of e^*. This is the case with the multiplicative form described above, where $U(e^*, \theta) = u(w_2) - \theta p(e^*)\left[u(w_2) - u(w_2 - L)\right]$ and $U_e(e^*, \theta) = -\theta p'(e^*)\left[u(w_2) - u(w_2 - L)\right]$. An increase in θ has therefore a negative impact on U and a positive impact on U_e so that condition (10) is respected. Figure 1 illustrates the situation when there are two possible values of θ: θ_1 and θ_2, and when the ambiguous loss probability is linear in θ.

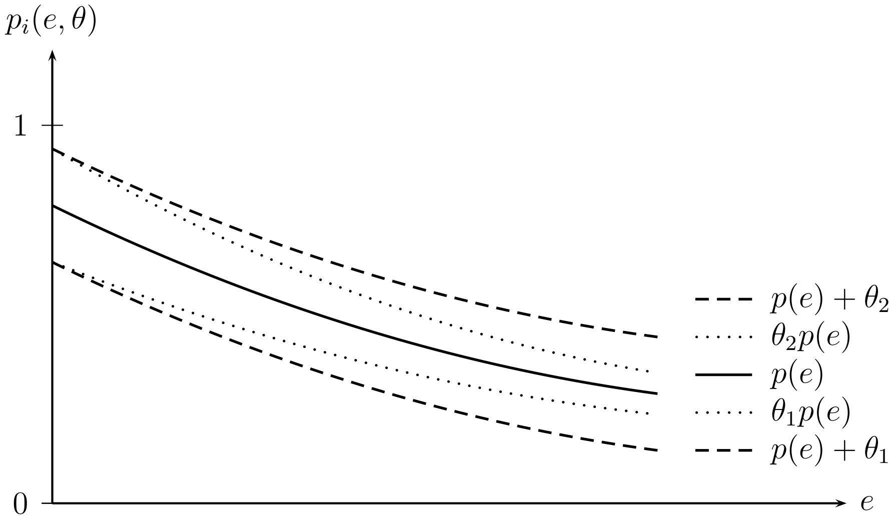

Figure 1: Examples of ambiguous loss probability functions that are linear in θ

As can be seen in Figure 1, when θ increases, from θ_1 to θ_2[17], different scenarios are possible. In the additive case, the slopes of the two dashed lines are exactly the same for any given level of effort. Ambiguity in this case is therefore constant. On the contrary, for the multiplicative form it is clear that the dotted curve for any given level of effort is steeper with θ_2 than with θ_1. Intuitively, this corresponds to a situation in which ambiguity decreases with the effort furnished and condition (10) is therefore respected.

The intuition behind these two examples is simple. In the absence of ambiguity, we know that a key determinant of the optimal level of self-protection is the slope of $p(e)$ (which determines the marginal benefit of effort). When ambiguity is intro-

[17]Note that in this example, $p(e)$ is the loss probability law considered by an ambiguity neutral agent and that the ambiguity averse DM associates the same prior belief to each value of θ, in such a way that $\theta_2 = -\theta_1$ in the additive case, and $\theta_2 = 2 - \theta_1$ in the multiplicative case.

duced, the DM does not know exactly in which situation he is: if his prior beliefs are equal, he considers he has one chance out of two to be confronted to a loss with probability $p(e, \theta_1)$, and one chance out of two to have $p(e, \theta_2)$. If the individual is ambiguity neutral, this situation does not affect him and the decision is taken by considering the expected law $p(e)$. However, if the agent is ambiguity averse, he will over-evaluate the less desirable outcome (i.e. the law $p(e, \theta_2)$) and hence take a decision by considering a law *somewhere above* the line $p(e)$. In the special case of infinite ambiguity aversion, corresponding to the Maxmin model of Gilboa and Schmeidler (1989), the DM takes his decision by considering the worst scenario $p(e, \theta_2)$.

The study of these two particular cases in which the probability is linear in parameter θ emphasizes the differences there are between the single and the two-period models. In the single period model, it is indeed impossible to sign the effect ambiguity aversion has on the optimal prevention, even when the probabilities are linear in the ambiguity parameter. In that situation in particular, the DM will always choose to reduce his demand of self-protection if the probability law is additive (Alary, Gollier, and Treich, 2013), while he will choose a higher level of protection if the probability law is multiplicative (Snow, 2011). This inability to obtain a general result is due to the fact that both the marginal cost and the marginal benefit of self-protection increase under ambiguity aversion. The net effect therefore depends on which one is more affected. In the two-period model analyzed in this paper however, ambiguity aversion only affects the marginal benefit, making it possible to draw general conclusions for the most plausible situations in which increasing the effort does not go along with an increase in the degree of ambiguity.

5 Conclusion

In this paper, I show that ambiguity aversion alone is not sufficient to sign the effect ambiguity has on the decision to (self-)insure or self-protect when two periods are considered. An additional condition defined as *ambiguity prudence attitude* – or non increasing absolute ambiguity aversion – is then studied, and it is shown that in most usual situations this condition tends to raise the incentive to undertake an effort (insurance or prevention) in the first period when non neutral attitude towards ambiguity is considered.

This paper thus enables to sign the effect of ambiguity aversion on (self-)insurance and self-protection under a plausible set of conditions. It is distinguishable from the other recent papers by Snow (2011) and Alary, Gollier, and Treich (2013) in which the marginal cost of effort is also affected by ambiguity, and that are therefore not able to draw general conclusions because of the conflicting effect ambiguity aversion has on marginal benefit and marginal cost.

Appendix

Proof of Proposition 3. This proof[18] is based on the following Lemma, that can be found in Gollier (2001).

Lemma 2. *Let ϕ be a twice differentiable, increasing and concave function: $\mathbb{R} \to \mathbb{R}$. Consider a probability vector $(q_1, ..., q_m) \in \mathbb{R}_+^m$ with $\sum_{\theta=1}^m q_\theta = 1$, and a function $f : \mathbb{R}^m \to \mathbb{R}$, defined as*

$$f(U_1, ..., U_m) = \phi^{-1} \left\{ \sum_{\theta=1}^{m} q_\theta \phi \left\{ U_\theta \right\} \right\}.$$

Let T be the function such that $T(U) = -\frac{\phi'\{U\}}{\phi''\{U\}}$. Function f is concave in $\mathbb{R}^m$ if and only if T is weakly concave in $\mathbb{R}$.

First, remark that programme (7) is convex if

$$V(e) = \phi^{-1} \left\{ \mathrm{E}_\theta \phi \left\{ p_i(e, \tilde{\theta}) u(w_{2,i}(e)) + \left[1 - p_i(e, \tilde{\theta})\right] \sum_{s \neq i} \pi_s u(w_{2,s}) \right\} \right\}$$

is concave in e.

Self-insurance ($p_i(e, \theta) = p_i(\theta)$ for all levels of e): Consider two scalars e_1 and e_2, and let $U_{j\theta}$ denote the second period expected utility conditional on θ, for a level of effort e_j: $U_{j\theta} = p_i(\theta) u(w_{2,i}(e_j)) + [1 - p_i(\theta)] \sum_{s \neq i} \pi_s u(w_{2,s})$. Under the notations above, $V(e_j) = f(U_{j1}, ..., U_{jm})$. Then, under concavity of u and $w_{2,i}$, and for any $(\lambda_1, \lambda_2) \in \mathbb{R}_+^2$ such that $\lambda_1 + \lambda_2 = 1$, we have:

$$\lambda_1 u(w_{2,i}(e_1)) + \lambda_2 u(w_{2,i}(e_2)) \leq u(\lambda_1 w_{2,i}(e_1) + \lambda_2 w_{2,i}(e_2)) \leq u(w_{2,i}(\lambda_1 e_1 + \lambda_2 e_2)).$$

[18] This proof is adapted from Gierlinger and Gollier (2008).

Multiplying the first and the third parts of this chain of inequalities by $p_i(\theta)$ and adding $[1-p_i(\theta)]\sum_{s\neq i}\pi_s u(w_{2,s})$ yields:

$$\lambda_1 U_{1\theta}+\lambda_2 U_{2\theta}\leq U_{\lambda\theta}\equiv p_i(\theta)u(w_{2,i}(e_\lambda))+[1-p_i(\theta)]\sum_{s\neq i}\pi_s u(w_{2,s})$$

for all θ, where $e_\lambda=\lambda_1 e_1+\lambda_2 e_2$. Because f is increasing in $\mathbb{R}^m$ if ϕ is increasing, this implies:

$$V(e_\lambda)=f(U_{\lambda 1},...,U_{\lambda m})\geq f(\lambda_1 U_{11}+\lambda_2 U_{21},...,\lambda_1 U_{1m}+\lambda_2 U_{2m}).$$

On the other side, if $-\phi'/\phi''$ is concave, by Lemma 2 we have:

$$\begin{aligned} f(\lambda_1 U_{11}+\lambda_2 U_{21},...,\lambda_1 U_{1m}+\lambda_2 U_{2m}) &\geq \lambda_1 f(U_{11},...,U_{1m})+\lambda_2 f(U_{21},...,U_{2m}) \\ &= \lambda_1 V(e_1)+\lambda_2 V(e_2). \end{aligned}$$

Combining these two results yields $V(\lambda_1 e_1+\lambda_2 e_2)\geq\lambda_1 V(e_1)+\lambda_2 V(e_2)$ implying that V is concave in e.

Self-protection ($w_{2,i}(e)=w_{2,i}$ for all levels of e): In this case, the proof is similar but $U_{j\theta}$ is now given by $U_{j\theta}=p_i(e_j,\theta)u(w_{2,i})+[1-p_i(e_j,\theta)]\sum_{s\neq i}\pi_s u(w_{2,s})$, and we exploit the convexity of $p_i(e,\theta)$ in e to obtain $\lambda_1 U_{1\theta}+\lambda_2 U_{2\theta}\leq U_{\lambda\theta}$. □

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