Prevention and precaution

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Abstract

This chapter surveys the economic literature on prevention and precaution. Prevention refers as either a self-protection activity – i.e. a reduction in the probability of a loss – or a self-insurance activity – i.e. a reduction of the loss –. Precaution is defined as a prudent and temporary activity when the risk is imperfectly known. We first present results on prevention, including the effect of risk preferences, wealth and background risks. Second, we discuss how the concept of precaution is strongly linked to the effect of arrival of information over time in sequential models as well as to situations in which there is ambiguity over probability distributions.

1. Introduction

The ways to protect against risks are numerous. An obvious way, as largely explained in this handbook, is to transfer risks to a third party via insurance or reinsurance, without modifying the risk itself. Another way to protect against risks is to act directly on the risk by altering either its occurrence or its consequences. This is what prevention is about. The study of prevention started with the earlier work of Ehrlich and Becker (1972). Since then, it has led to a flourishing literature in the field of risk and insurance economics. It seems then appropriate to include an entire new chapter about prevention in this handbook on insurance economics.

In day-to-day language, prevention is very similar to precaution. In economics, however, prevention is usually a static concept while precaution is fundamentally a dynamic one. Indeed, models of precaution generally involve a sequence of decisions with arrival of information over time. Therefore, although the concepts of prevention and precaution are closely connected, we will see that their formal analyses have evolved very differently in the economics literature.

This chapter offers a survey of both the economics of prevention and precaution. We begin by reviewing the early work on prevention in section 2. We start first by presenting the basic model of prevention with a monetary risk under the Expected Utility (EU) framework. We present the roles of individual preferences in explaining optimal prevention, and more specifically the roles of risk aversion and prudence. We also look at wealth effect and more general distribution of loss than the two-state model. We then consider other contexts such as non-monetary risk, the presence of background risk and a non-expected utility environment. In section 3, we address the concept of precaution. We first relate this concept to the Precautionary Principle, then present the early literature on the irreversibility effect and option values and finally discuss the more recent literature, including the one related to climate change policy as well as to ambiguity. Lastly, a short conclusion is provided.

2. Prevention

Prevention is a risk-reducing activity that takes place ex-ante, i.e. before the loss occurs. As risk is defined through the size and probability of the potential loss, prevention can either impact the size of the potential loss, its probability or both. When it modifies the size of the loss, it is referred to as self-insurance or loss reduction. When it modifies the probability of the loss it is referred to as self-protection or also loss prevention. An activity reducing both the size and the probability of loss is referred to as self-insurance-cum-protection (Lee, 1998). For example, sprinkler systems reduce the loss from fires and car seat belts reduce the degree of injury from car crash; stronger doors, locks or bars on windows reduce the probability of illegal entry. Naturally, as observed in practice, many actions individuals take modify both the size and the probability of the potential loss. For instance, high quality brakes reduce both the probability of an automobile accident and the magnitude of a loss if an accident occurs.

The academic literature on prevention dates back to the earlier work of Ehlrich and Becker (1972). In their seminal paper they examined, within the EU framework, the interaction between market insurance, self-insurance and self-protection. In line with intuition based on the moral hazard problem, they showed that market insurance and self-insurance are substitutes. Yet, surprisingly, the analysis of self-protection led to different results since they derived that market insurance and self-protection could be complements depending on the level of the probability of loss. Thus, the presence of market insurance may, in fact, increase self-protection activities relative to a situation where market insurance is unavailable. This work has led to many discussions and extensions on the optimal individual behaviour with respect to self-insurance and self-protection.

In order to avoid any confusion in terminology, it is important to stress the similarity between prevention and the concept of willingness-to-pay (WTP). WTP is the amount an individual is willing to pay to reduce either the size of the loss or the probability of the loss.

Indeed as stressed by Chiu (2000), the concept of WTP to reduce the probability of loss is equivalent to investigating the optimal choice of self-protection given an assumed relationship between self-protection spending and the loss probability. Dachraoui *et al*. (2004) confirmed this equivalence by showing that self-protection and WTP to reduce the probability share the same properties. In the same vein, the WTP to reduce the size of a loss is equivalent to investigating the optimal choice of self-insurance given an assumed relationship between self-insurance spending and the loss size. Throughout this chapter, when using the term WTP we will make reference to the WTP to reduce the probability, unless otherwise specified.

2.1. Expected utility model with a monetary risk

2.1.1. Self-insurance and self-protection

Consider an individual with initial wealth w_0 subject to a risk of loss of size L_0, with $0 \le L_0 \le w_0$. The loss occurs with probability p_0 $(0 < p_0 < 1)$. This individual has an increasing vNM utility function, u $(u' > 0)$. The individual can engage in self-insurance activities to reduce the size of the loss, should it occur. Let y denote the level of self-insurance. Its effect is described by the differentiable function $L(y)$ which relates the size of the loss to the level of self-insurance activity, with $L(0) = L_0$, $L'(y) < 0$ and $L''(y) > 0$ for all $y \ge 0$, i.e. reduction in the size of loss becomes more difficult as self-insurance activities increase. The cost of self-insurance, $c(y)$, is represented by a monotonic and convex function with the usual assumption that $c(0) = 0$, $c'(y) > 0\ \forall y > 0$ and $c''(y) > 0\ \forall y \ge 0$. The objective of the individual is to maximize his expected utility given by:

$$V(y) = p_0 u(w_0 - c(y) - L(y)) + (1 - p_0)u(w_0 - c(y)) \tag{1}$$

The first-order condition (FOC) for a maximum is

$$\frac{dV(y)}{dy} = -p_0(c'(y) + L'(y))u'(B(y)) - (1 - p_0)c'(y)u'(G(y)) = 0 \tag{2}$$

where $B(y) = w_0 - c(y) - L(y)$ and $G(y) = w_0 - c(y)$.

The FOC implies that $-L'(y)$ must be greater than $c'(y)$ which means that the magnitude of the potential marginal benefit of self-insurance must be at least as high as the cost of the increase in *y*. Assumptions made on $L(y)$ and $c(y)$ guarantee that the second-order condition is satisfied for all risk averse individuals ($u''<0$).

Let's denote y^* the optimal level of self-insurance. From equation (2), it is such that:

$$-c'(y^*)\left[p_0u'(B(y^*)+(1-p_0)u'(G(y^*))\right]=p_0L'(y^*)u'(B(y^*)) \qquad (3)$$

The left-hand term of equation (3) represents the marginal cost of self-insurance while the right-hand term represents its marginal benefit. It can be seen that an investment in self-insurance increases wealth in the bad states of nature at a cost of reduced wealth in the good state. Self-insurance is very close to market insurance and results on market insurance usually apply to self-insurance.

Suppose now that the individual can invest in self-protection activities *x* that reduce the probability of loss, but do not affect the size of the loss L_0 should it occur. The probability of loss is a decreasing function of the level of self-protection whose marginal productivity is increasing, i.e. $p(0)=p_0$, $p'(x)<0$ and $p''(x)>0$ for all $x\geq 0$. In this case, the individual's expected utility is:

$$V(x)=p(x)u(w_0-c(x)-L_0)+(1-p(x))u(w_0-c(x)) \qquad (4)$$

The first-order condition for a maximum is

$$\frac{dV(x)}{dx}=-c'(x)\left[p(x)u'(B(x))+(1-p(x))u'(G(x))\right]-p'(x)\left[u(G(x))-u(B(x))\right]=0 \qquad (5)$$

where $B(x)=w_0-c(x)-L_0$ and $G(x)=w_0-c(x)$.

Assumptions made on $c(x)$ and $p(x)$ are not sufficient to guarantee that the second order condition for a maximum is satisfied (i.e. $V''(x)<0\ \forall x$). For sake of simplicity, it is assumed that the functions *u*, *c*, *p*, and the parameters w_0 and L_0 are such that $V''(x)<0\ \forall x$ (see for instance Jullien *et al.* 1999). This ensures a unique solution to the individual maximization problem x^* such that $V'(x^*)=0$ that can be also written as:

$$-c'(x^*)\lfloor p(x^*)u'(B(x^*)) + (1-p(x^*))u'(G(x^*))\rfloor = p'(x^*)\lfloor u(G(x^*)) - u(B(x^*))\rfloor \qquad (6)$$

The left-hand term in equation (6) is the expected marginal cost (in terms of utility) of self-protection activities. The right-hand term is the expected marginal benefit (in terms of utility) from the resulting decrease in the loss probability.

An investment in self-protection modifies probabilities so that the good state of nature becomes more likely, but it also reduces final wealth in every state of nature. This trade-off between reducing the probability of loss and reducing final wealth may not necessarily be appreciated by all individuals as explained in the next section. We will see that restrictions are needed on the utility function, on the distribution function or on the loss function for an individual to pursue self-protection.

Before doing so, let's stress that self-protection and self-insurance can be analyzed using the concept of WTP. WTP makes it possible to evaluate the monetary value one is ready to forgo to benefit from a reduction in either the loss or the probability of loss (Jones-Lee, 1974). This concept is often used to measure the benefit of prevention.

Let's denote *t* the maximum amount of money the individual is willing to pay to benefit from a reduction of the loss from L_0 to L_1 with $L_1 < L_0$. *t* verifies the following equation:

$$p_0 u(w_0 - L_1) + (1-p_0)u(w_0) = p_0 u(w_0 - t - L_0) + (1-p_0)u(w_0 - t) \qquad (7)$$

Let's denote *d* the maximum amount of money the individual is willing to pay to benefit from a reduction of the probability of loss from p_0 to p_1 with $p_0 < p_1$. *d* verifies the following equation:

$$p_0 u(w_0 - L_0) + (1-p_0)u(w_0) = p_1 u(w_0 - d - L_0) + (1-p_1)u(w_0 - d) \qquad (8)$$

Note that the WTPs *t* and *d* can also be expressed in terms of marginal rate of substitution in the case of infinitesimal change in risk. This is especially true for mortality risk or in studies on the value of statistical life (see section 2.2.1).

Various authors (e.g. Chiu (2005) and Dachraoui *et al.* (2004)), showed that the optimal level of self-insurance y^* and *t*, respectively the optimal level of self-protection x^* and *d*, share similar properties.

2.1.2. Optimal prevention and risk aversion

Dionne and Eeckhoudt (1985) investigated how self-insurance and self-protection decisions reacted to an increase in risk aversion defined through an increasing and concave transformation of the utility function. They considered a simple two state model in which the severity of the possible loss is fixed as detailed in the previous section. They showed that self-insurance increases with risk aversion, while an increase in risk aversion does not always induce a higher level of self-protection.

Following Pratt (1964), a more risk-averse individual whose utility function v ($v'(w) > 0\ \forall w$ and $v''(w) < 0\ \forall w$) can be represented by a concave transformation, k, of u such as $v(w) = k(u(w))$ with $k'(w) > 0$ and $k''(w) < 0$ for all w.

The first-order condition of agent with a utility function v evaluated at y^* is:

$$-p_0(c'(y^*) + L'(y^*))k'(u(B(y^*))u'(B(y^*)) - (1 - p_0)c'(y^*)k'(u(G(y^*))u'(G(y^*)) \quad (9)$$

Equation (9) is positive because $k'(u(B(y^*)) > k'(u(G(y^*))$ under the concavity of k. Hence an increase in risk aversion always induces an increase in self-insurance activity since it increases its marginal benefit and decreases its marginal cost.

In the case of self-protection, the first-order condition for an agent with a utility function v evaluated at x^* is:

$$\begin{aligned} &-c'(x^*)\left[p(x^*)k'(u(B(x^*))u'(B(x^*)) + (1 - p(x^*))k'(u(G(x^*))u'(G(x^*))\right] \\ &-p'(x^*)\left[u(G(x^*)) - u(B(x^*))\right] \end{aligned} \quad (10)$$

Contrary to what is obtained in the preceding case, $k' > 0$ and $k'' < 0$ are not sufficient to compare the two levels of self-protection. However, in the specific case of a quadratic utility function, Dionne and Eeckhoudt (1985) showed that self-protection increases (decreases) with risk aversion for an initial probability of loss strictly inferior (superior) to one half. An intuition of this result is that variance increases (decreases) with the probability when the probability is strictly inferior to one half. Even if the variance is not a perfect measure of risk, this provides an intuition of the results. Their work has led to an extensive literature on the role of individual preferences in explaining optimal prevention decision, and in particular on the roles of risk aversion and prudence.

Hiebert (1989) extended Dionne and Eeckhoudt (1985)'s result of self-insurance to the case where either the magnitude of prospective loss, or the productivity of self-insurance, is uncertain. He showed that an increase in risk aversion always leads to an increase in self-insurance when the potential loss is random, while this is not necessarily the case when the effectiveness of self-insurance is random. This happens since an increase in self-insurance reduces the variance of the (conditional) loss in the case of random loss, while it increases the variance in the case of random effectiveness.

Briys and Schlesinger (1990) went further into the analysis of self-insurance and self-protection as risk-reducing activities. If the cost of self-insurance and self-protection is assumed actuarially fair, i.e. that expected wealth remains constant for all levels of self-insurance or self-protection, they showed that an increase in self-insurance induces a mean-preserving contraction in the sense of Rothschild and Stiglitz (1970). However, this is not the case for self-protection which is clearly neither a mean-preserving contraction nor a mean preserving spread. As a more risk averse would optimally invest more in risk reducing activities, he will invest more in self-insurance but not necessarily in self-protection as it is not necessarily risk reducing.

Bryis *et al*. (1991) investigated whether these results were robust for the case of non-reliability of prevention, i.e. in the case where the effectiveness of prevention was uncertain. In the case of self-insurance, they showed that the positive relationship between risk aversion and self-insurance no longer holds. This happens since the risky self-insurance helps to control one risk, but creates another one - namely the risk of wasting money on self-insurance activities that do not work. Since the real test of workability comes only during the loss experience, the individual cannot be certain whether or not self-insurance will be effective until a loss is experienced. Thus a more risk averse individual may conceivably decide to reduce the investment in self-insurance, so as to improve the worst possible state. They also showed that the relation between risk aversion and self-protection was still ambiguous under non-reliability.

Lee (1998) added to this literature by examining the effect of increased risk aversion on self-insurance-cum-protection (SICP) activity which influences both the probability and the size of the potential loss. He showed that the effect depends in part on the shape of the loss function and that of the probability function. In particular, if the marginal reduction in a loss in the bad state outweighs the marginal increase in the cost of SICP expenditures, more risk-averse individuals invest more in SICP. The intuition for this result is that, under the above condition, an increase in SICP expenditures makes the distribution of utility less risky or induces second-order stochastic dominance in the distribution of utility.

Eeckhoudt *et al*. (1997) showed that the WTP to reduce the probability of a financial loss is not necessarily increasing in the Arrow–Pratt measure of risk aversion depending on conditions on individual preferences. For instance, a risk averse individual with CARA utility function can have a higher WTP than a risk neutral individual. In the same vein, Jullien *et al*. (1999) showed that self-protection increases with risk aversion if and only if the initial probability is less than a utility-dependent threshold.

Courbage and Rey (2008) addressed the links between risk aversion and WTP in the case of small risks, i.e. risks defined by small losses that can be approximated by second order Taylor series developments. In this environment, they showed that the WTP increases with risk aversion if the loss probability is inferior to one half. If this probability is superior to one half, the higher the initial loss probability, the more efficient prevention activity has to be to increase the WTP of a more risk averse individual.

2.1.3. The role of prudence in self-protection activities

As shown by Dionne and Eeckhoudt (1985), in the special case of quadratic utility, the probability threshold under which self-protection increases with risk aversion is exactly one half. As quadratic utility function is characterized by a third derivative of the utility function being nil, the sign of the third derivative may drive self-protection activities. Eeckhoudt and Gollier (2005) showed that actually both risk aversion and prudence (as defined by the third derivative of the utility function being positive) play a role in explaining self-protection activities. Since risk aversion tends to raise self-protection when the probability is close to zero, and to lower it when this probability is close to unity, Eeckhoudt and Gollier (2005) concentrated on the intermediary case where the probability of loss is around one half. In such a case, they showed that a prudent agent, either risk averse or risk lover will exert less self-protection than a risk neutral one (which by definition is prudent neutral). They explained this result by the fact that less effort has no impact on the measure of risk at the margin, whereas it raises the precautionary accumulation of wealth which is helpful to face future risk.

Chiu (2000) using a WTP approach obtained a related result. He showed that a risk averse individual with a vNM utility function $u(x)$ is willing to pay more than the expected reduction of loss for a reduction in the probability of loss if the initial probability of loss is below a threshold determined by $-u'''(x)/u''(x)$ which is known as the index of absolute prudence.

Building on these works, Chiu (2005) showed that, identifying individuals with their vNM utility function, $-v'''(x)/v''(x) \leq -u'''(x)/u''(x)$, implies that individual *v*'s optimal choice of self-protection expenditure is larger than individual's *u*, provided that the marginal expenditure in self-protection is equal to the marginal reduction in the expected loss. Chiu (2005) also stressed that the effect of a mean-preserving increase in self-protection is a special combination of downside risk increase and a mean-preserving contraction satisfying the conditions for $-u'''(x)/u''(x)$ to measure *u*'s strength of downside risk aversion relative to his own risk aversion. Therefore, an individual whose aversion to downside risk is weaker relative to his preference for a mean-preserving contraction will opt for such an increase in self-protection expenditure.

Dachraoui *et al*. (2004) defined even more restrictive conditions on the utility function to exhibit an exogenous threshold probability over which a more risk averse individual invests more in self-protection activities and has a higher WTP. They used the concept of mixed risk aversion (MRA) introduced by Caballé and Pomansky (1996) to define "more risk averse MRA". An individual is more risk averse MRA than another if he is more risk averse, more prudent, more temperate, etc. They showed that if an agent is more risk averse MRA than another then he will select a higher level of self-protection and have a higher WTP than the other individual if and only if the loss probability is lower than one-half.

In a related paper, Dionne and Li (2011) proved that the level of self-protection chosen by a prudent agent is larger than the optimal level of self-protection chosen by a risk neutral agent if absolute prudence is less than a threshold that is utility independent, and stays the same for all agents. This threshold is equal to "the marginal change in probability on variance per third moment of loss distribution". The intuition is that the level of self-protection chosen by a prudent agent is larger than the optimal level of self-protection chosen by a risk neutral agent when the negative effect of self-protection on the variance is larger than the positive effect on the third moment of the loss distribution.

All these models consider a one-period framework, i.e. they implicitly assume that the decision to engage in self-protection activities and its effect on the loss probability are simultaneous. However, it often happens that the decision to engage in self-protection activities precedes its effect on the probability calling for the use of a two-period framework. Within a two-period framework, Menegatti (2009) showed that the role of prudence in explaining self-protection activities was opposite to the case of a one-period framework as described by Eeckhoudt and Gollier (2005). In particular he showed that for a loss probability equal to one half, a prudent agent, whatever his risk aversion, chooses a higher level of self-protection than a risk neutral agent (who by definition is prudent neutral). The explanation comes from the Eeckhoudt and Schlesinger (2006) notion of risk apportionment under which a prudent agent desires a larger wealth in the period where he bears the risk. In a two-period framework, more effort reduces wealth in the first period when there is no risk and increases expected wealth in the second period when the agent bears the risk, which is appreciated by a prudent agent.

2.1.4. Prevention, insurance and wealth effect

Prevention and insurance

Ehlrich and Becker (1972) were the first to address the relationship between insurance and respectively self-insurance and self-protection. They showed that market insurance and self-insurance are substitutes in the sense that an increase in the price of insurance, the probability of loss being the same, decreases the demand for market insurance and increases the demand for self-insurance. This is the case as insurance and self-insurance both decrease the size of the loss. This does not apply to self-protection which can be either a substitute or complement to insurance. Indeed, market insurance has two opposite effects on self-protection. On the one hand, self-protection is discouraged because its marginal gain is reduced by the reduction of the difference between the incomes and thus the utilities in different states; on the other hand, it is encouraged if the price of market insurance is negatively related to the amount spent on protection through the effect of these expenditures on the probabilities.

Boyer and Dionne (1983) derived some new propositions concerning the choice among self-insurance, self-protection and market insurance under alternative market conditions. In particular, they showed that risk averse individuals prefer self-insurance to market insurance under perfect information about self-protection if market insurance and self-insurance are associated with the same variation in the expected net loss and are equally costly.

Chang and Ehrlich (1985) extended their analysis by showing that if the price of insurance were responsive to self-protection, then the latter would induce a substitution away from self-insurance and towards market insurance, as long as the utility function exhibits constant or decreasing absolute risk aversion (see also Boyer and Dionne (1989) for a related result).

Briys *et al*. (1991) addressed the links between market insurance and self-insurance in the case where the effects of self-insurance are not perfectly reliable. They implicitly assumed that the potential non-performance of self-insurance is known by the consumer, who assigns a probability distribution to the effectiveness of the tool. In such a case, they showed that market insurance and self-insurance may be complements. As the authors stressed it, the intuition behind this result is not clear and might be best understood by focusing on the worst possible outcome for the consumer. This occurs in the state of nature where both a loss occurs and self-insurance fails. In this case, the consumer not only suffers the higher loss, but also loses the investment in self-insurance. At a higher price level of insurance, less insurance is purchased and so more of the loss is borne out of pocket. By decreasing the investment in self-insurance, the consumer can at least improve the worst possible state of the world.

More recently, Kunreuther and Muermann (2008) investigated the optimal investment in self-protection of insured individuals when they face interdependencies in the form of potential contamination from others. They showed that if individuals cannot coordinate their actions, then the positive externality of investing in self-protection implies that, in equilibrium, individuals underinvest in self-protection. They also showed that limiting insurance coverage through deductibles can partially internalize this externality and thereby improve individual and social welfare.[1]

Prevention and wealth effect

The effect of a change in wealth on self-insurance is the same effect as a change in wealth on insurance. It depends on how risk aversion reacts to a change in wealth. Lee (2010) showed that an increase in initial wealth decreases (increases, does not change) self-insurance against wealth loss if the utility function satisfies DARA (IARA, CARA). The intuition is that with DARA, an increase in initial wealth reduces the marginal utility benefit of an increase in self-insurance more than the marginal utility cost. Therefore, it decreases the incentives to invest in self-insurance. With IARA, the opposite holds, and an increase in initial wealth increases the incentives to invest in self-insurance. With CARA such wealth effects are absent.

Results regarding self-protection are less clear-cut since an increase in initial wealth decreases both the marginal utility benefit and marginal utility cost of self-protection, it may

[1] See also Schlesinger and Venezian (1986) for an analysis of consumer welfare in a model considering both insurance and self-protection under various market settings.

increase or decrease self-protection. Sweeney and Beard (1992) showed that the effect of an initial wealth increase depends on both the probability of loss and the characteristics of the agent's absolute risk-aversion function. In particular, the length of the interval of probability values over which self-protection is a normal good for a person depends in a complex fashion on the shape of that person's risk-aversion function over the entire interval of wealth between the two possible outcomes. The authors also looked at the effect of a change in the size of the potential loss and provided plausible restrictions on risk preferences under which an increase in the size of the potential loss leads to increased self-protection.

2.1.5. More general distributions of loss

The previous works considered a two-state model, i.e. either a loss (the bad state) or no loss (the good state) occur. However, results in the two-state case do not necessarily carry over to many states and this is especially true for self-insurance. The difficulty is that self-insurance does not necessarily reduce larger losses in the bad states more effectively than smaller losses in the good states. Rather, the effectiveness of a given self-insurance investment across different states depends on its technology and the nature of the losses. Self-insurance may thus not act as insurance and wealthier individuals may invest less or more in self-insurance. Lee (2010) provided some sufficient conditions under which self-insurance is an inferior good and some conditions under which it is a normal good. This depends on the single-crossing condition in Diamond and Stiglitz (1974) under which more risk-averse individuals increase the level of the control variable.

Lee (1998) also examined the effect of increased risk aversion on self-insurance-cum-protection (SICP) activity in the case of a general model with many states of the world. He showed that contrary to the two-state model, the condition that the marginal reduction in a loss in the bad state outweighs the marginal increase in the cost of SICP expenditures is not sufficient to have more risk-averse individuals investing more in SICP. To obtain this result, an additional condition concerning the shape of the distribution function is needed. This additional condition ensures that an increase in SICP decreases wealth or utility in all favorable states while increasing wealth or utility in all unfavorable states. In this way, an increase in SCIP contracts the distribution of utility towards the mean.

Recently, Meyer and Meyer (2011) studied the relationship between risk aversion and prudence and the demand for self-protection outside the usual assumption that the loss variable follows a Bernoulli distribution, and that changes in the level of self-protection are mean-preserving. Their analysis replaced these two strong conditions with one which is more general. This modification includes representing a change in the level of self-protection using the procedure developed by Diamond and Stiglitz (1974) to represent changes in the riskiness of a random alternative. The self-protective acts that can be considered are changed from those that are mean-preserving to those that are mean utility preserving for an arbitrary utility function. Their analysis showed that when the risk changes are equal in size, then all that matters is whether the decision-maker's absolute risk aversion measure increases faster or slower than does the absolute risk aversion measure of the reference person. When these risk changes are not equal in size, whether the decision-maker is more or less risk averse than the reference person also enters into the decision.

2.2. Other contexts

2.2.1. Non-monetary risk

The previous literature focuses on financial risks, i.e. it considers individual preferences as dependent only on wealth. It does not capture situations for which risks are not monetary and in particular health risks. Indeed, one important feature of health as a good is its irreplaceable feature (Cook and Graham, 1977), i.e. a good for which there is no substitute on the market. This calls for using a bivariate utility function to represent individual preferences where arguments of the function are, respectively, wealth and health. The use of bivariate utility functions makes it possible to dissociate satisfaction of wealth in case of illness and of good health.

Lee (2005) investigated how a change in initial wealth modifies the level of prevention against a health loss using bivariate utility function. He showed that the sign of the cross derivative of the utility function plays a crucial role. If this sign is positive, then an increase in initial wealth increases self-insurance against health loss. The reason is simply that under a positive sign of the cross derivative, an increase in initial wealth increases the marginal utility of health giving greater incentives to invest in self-protection. As for self-protection, Lee (2005) also showed that under a positive sign of the cross derivative, an increase in initial wealth increases self-protection against health loss. It is the case because under this condition, an increase in initial wealth increases the marginal benefit of prevention and decreases its marginal cost. These predictions contrast with the result in the standard model with wealth loss only.

Courbage and Rey (2006) looked at the link between self-protection and the concept of fear of sickness (FS). FS measures the “degree of future pain” induced by the occurrence of the illness, where pain is measured via a decrease in utility. They showed that when an individual has a higher FS than another, then lower prudence exhibited by the first individual over the second is a sufficient condition to pursue more prevention, whatever the distribution of the probability of illness. The story behind this result is that FS affects the marginal benefit of prevention while its marginal cost depends on prudence.

There is also an important literature on the value of a statistical life (VSL). The VSL is extensively used in cost-benefit analysis in order to obtain a monetary value of life-savings benefits. The VSL can be seen as a WTP per unit of reduction in a mortality risk. To obtain a formal expression of the VSL, consider a simple static model such as

$$(1-p)u(w_0) + pv(w_0) \tag{11}$$

where $u(.)$ is the utility if alive and $v(.)$ is the utility if dead. This simple model, introduced first by Drèze (1962) and afterwards by Jones-Lee (1974), has been commonly used in the literature (see, e.g. Viscusi and Aldy, 2003). Within this model, it is traditionally assumed that $u(.) > v(.)$, $u' > 0$, $v' \geq 0$, $u' > v'$, $u'' \leq 0$ and $v''(.) \leq 0$. That is, state-dependent utilities are increasing and concave. Moreover, utility if alive is larger than utility if dead and marginal utility if alive is larger than marginal utility if dead. The VSL is formally the marginal rate of substitution between wealth and survival probability, i.e. the slope of the indifference curve at (w_0, p). It is defined by:

$$\text{VSL} = \frac{dw_0}{dp} = \frac{u(w_0) - v(w_0)}{(1-p)u'(w_0) + pv'(w_0)} > 0 \tag{12}$$

Note that the VSL may vary across individuals since it depends on w_0, p, and on the shape of the utility function through u and v. In particular, under our assumptions it is easy to see that the VSL increases in wealth. It also increases in the baseline probability of death *p*, an effect coined the “dead-anyway effect” (Pratt and Zeckhauser 1996).

2.2.2. Prevention and background risk

Briys and Schlesinger (1990) addressed the issue of whether the presence of a background risk would modify the relation between risk aversion and self-insurance. Using the stronger measure of risk aversion proposed by Ross (1981) they showed that more risk averse individuals invest more in self-insurance activities when their initial wealth is also random.

Courbage and Rey (2008) showed in the case of small risks that either DARA or risk vulnerability is required to have an increase in the WTP to reduce the probability of loss in the face of an independent unfair background risk of loss, depending on the support of the background risk and on the level of the probability of loss.

Bleichrodt *et al*. (2003) used a bivariate utility function depending on wealth and health to address how the willingness to pay to decrease the probability of illness reacts to the presence of co-morbidity. They showed that the willingness to pay for health improvements increases with the severity and probability of occurrence of co-morbidities. This result is obtained under mild restrictions on the shape of the utility function and some additional assumptions of the correlation between the two conditions. In the same vein, Eeckhoudt and Hammitt (2001) examined the effects of background mortality and financial risk on the value of statistical life (VSL). They showed that under reasonable assumptions about risk aversion and prudence with respect to wealth in the event of survival and with respect to bequests in the event of death, background mortality and financial risks decrease VSL. In addition, they showed that results depend on the size of the risks. Indeed, the effects of large mortality or financial risks on VSL can be substantial but the effects of small background risks are negligible.

Finally, in two simultaneous and independent papers, Courbage and Rey (2011) and Eeckhoudt *et al*. (2011) looked at the impact of both the presence and an increase of a background risk on optimal self-protection activities using a two-period model as introduced by Menegatti (2009). While Eeckhoudt *et al*. (2011) considered the background risk only in the second period, Courbage and Rey (2011) considered various other configurations of background risk, defined either in the first or second period, as state-independent or state-dependent, or in both periods simultaneously. The introduction of a first period background risk is shown to reduce self-protection under prudence in this period, while it increases self-protection if the background risk is introduced in the second period under prudence in the second period. In the case of state-dependent background risks, risk aversion only drives the results. The effect of an increase in the background risk, as defined through *nth*-order stochastic dominance, naturally depends on the configuration of the background risk and is driven by the signs of the successive derivatives of the utility function to any order *n*.

2.2.3. Prevention and non-expected utility models

Many empirical contradictions of the independence axiom (see, e.g. Allais, 1953; Ellsberg, 1961) have led economists to call into question the global validity of EU models and to develop new theories of choice under risk. The question is then whether existing results are robust to new models of behaviour under risk. An important class is the Rank Dependent Expected Utility's (RDEU) developed by Quiggin (1982) and Yaari (1987). Under RDEU, probabilities are distorted and treated in a nonlinear way. The weight given to an event depends on the ranking with respect to the others allowing individuals to overweight or underweight bad or good events.

Konrad and Skaperdas (1993) studied the properties of self-insurance and self-protection under RDEU. They showed that many of the comparative statics results that hold for expected utility carry over to RDEU. In particular, they showed that more risk-averse individuals (as defined through the shapes of both the utility function and probability transformation function) have a higher demand for self-insurance, even with background risk. Self-insurance demand in case of multiplicative risk increases (decreases) with wealth if the individual has increasing (decreasing) relative risk aversion. The generally ambiguous results on risk aversion and self-protection carry over also for RDEU. However, for risks that occur with very small or very large probabilities, the comparative statics of increases in risk aversion are qualitatively determined.

Courbage (2001) reconsidered the relationships existing between market insurance and respectively self-insurance and self-protection in the context of Yaari's Dual Theory (DT). While EU assigns a value to a prospect by taking a transformed expectation that is linear in probabilities but non-linear in wealth, DT provides the counterpoint since it reverses the transformation. The results for EU on self-insurance carry over to DT. Market insurance and self-insurance are substitutes, even with a background risk. They can be complements when reliability of self-insurance activity is not guaranteed. The generally ambiguous link between market insurance and self-protection carries over also to DT. However, this result is easily explainable by the role of the transformation function in under- or overestimating probabilities and their variation. He also considered the situation where the insurance company may not price the premium according to effective self-insurance and self-protection activities. Naturally, in that case market insurance and self-protection are substitutes.

Langlais (2005) looked at the links between risk aversion and the WTP without the EU assumptions. Introducing minimal assumptions on the individual preferences, he showed that the WTP for both a first-order stochastic dominance and second-order stochastic dominance reduction of risk is the sum of a mean effect, a pure risk effect and a wealth effect. Depending on the sign of these three effects, the WTP of a risk-averse decision-maker may be lower than the WTP of a risk-neutral one, for a large class of individual preferences' representation and a large class of risks.

Bleichrodt and Eeckhoudt (2006) considered also self-protection activities in the context of RDEU but in the specific case of WTP for reductions in the probability of health loss using univariate utility function. They compare the WTP under RDEU to the one under EU. They find that the introduction of probability weighting leads to an increase in the WTP for reductions in health risks when the individual underweights the probability of being in good health and is relatively sensitive to changes in loss probability. When the individual overweights the probability of being in good health and is relatively insensitive to changes in loss probability, probability weighting decreases the WTP for reductions in health risks. Their results show that the effect of probability weighting can be large and may lead to unstable estimates of WTP for the probabilities generally used in empirical elicitations of WTP.

Recently, Etner and Jeleva (2012) as well used the RDEU model to study the impact of risk perception on self-protection in the context of health risks. They highlighted the importance of the shape of the probability transformation in explaining medical prevention decisions.

Finally, note that self-protection and self-insurance activities have also been studied in models of ambiguity preferences under which the decision-maker is assumed to be uncertain about the probability of the loss occurring. We decided to present these works in section 3.5.4. dealing with the concept of precaution since, as it will be explained, precaution refers to models in which today's decision is affected either by the receipt of information in the future or by ambiguity over loss probability distributions.

3. Precaution

In this section, we argue that a fundamental difference between prevention and precaution rests on the difference between risk and information. To study precaution, the theoretical literature has traditionally considered a two-decision model and has examined the anticipated effect of receiving more information in the future on the first decision. This effect was first studied in the 1970s, and was initially referred to as the irreversibility effect by Henry (1974). It also relates to the notion of (quasi-)option value as introduced by Arrow and Fisher (1974). It was then generalised in the 1980s, most notably after Epstein (1980) provided a technique for developing the comparative statics of information in a sequential model. More recently this effect was related to the study of climate policy by, for example, Ulph and Ulph (1997) and to the Precautionary Principle by Gollier *et al*. (2000).

3.1. Prevention vs. precaution

The origin of the word prevention relates to the idea of "acting before". Prevention may be understood as an anticipative measure taken in order to avoid a risk, or at least to attempt to limit its damages. In contrast, the latin root of the word precaution refers to the idea of "watching out". It thus concerns a more diffuse threat, suggesting that there is only a potential risk. Consistent with this idea, it is often said that the Precautionary Principle (PP) introduced a new standard of risk management when the very existence of a risk is not scientifically established. The principle 15 of the 1992 Rio Declaration defines the PP as follows: "*Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation*".[2]

Since Knight (1921), it is usual to make a distinction between a risk, characterized by an objective probability distribution, and uncertainty, which is not related to any precise probability distribution. And it is often said in a colloquial sense that prevention is related to the management of risk while precaution is related to the management of uncertainty. Yet, without a clear definition of risk and uncertainty, this distinction is hardly operational. In fact, in the classical Savagian expected utility framework there is essentially no difference between risk and uncertainty (Savage, 1954; De Finetti, 1974). Agents make decisions based on their subjective beliefs, but the decision-making framework remains the same independent of agents' beliefs.

The key point, however, is that one can propose a formal distinction between risk and uncertainty within the Savagian framework. This distinction relates to the possibility of acquiring information over time. A situation of uncertainty can be thought of as a situation in which more information is expected to arrive in the future. Formally, the subjective probability distribution that the decision-maker holds in the initial period is expected to be

[2] Similar definitions have been included in international statements of policy including, e.g. the 1992 Convention on Climate Change, the 1992 Convention on Biological Diversity, the Maastricht Treaty in 1992/93, and the 2000 Cartagena Protocol on Biosafety. The PP has also been enacted in the national law of several countries, especially in Europe. In France for instance, the PP was included in 2005 in the French Constitution, that is at the highest juridical national level.

updated over time. This is the *lack of full scientific certainty* advocated by the PP, suggesting that there will be scientific progress in the future. With the accumulation of knowledge, uncertainty resolves, at least partially, allowing for a revision of beliefs. This leads us to recognize that precaution is not a static concept.

To sum it up, prevention can be viewed as a static concept that refers to the management of a risk at a given time and given a stable probability distribution. In contrast, precaution is a dynamic concept that recognizes that there is scientific progress over time. Precaution thus could be interpreted as a cautious and temporary decision that aims at managing the current lack of definitive scientific evidence. The theoretical question underlying the literature on precaution is therefore how the prospect to receive information in the future affects today's decisions. This question was initially addressed in a model where decisions can be irreversible.

3.2. The "irreversibility effect"

The development of an irreversible project is considered. The project is irreversible in the sense that once it is developed it cannot be stopped, or at an infinite cost. If the project is developed immediately, the current net benefit is equal to $b > 0$. But the project is risky in the long run, and its future net benefit is represented by the random variable $\tilde{\theta}$. Under risk-neutrality and no discounting, the traditional cost-benefit rule is that the project should be adopted now if and only if the sum of expected net benefits is positive, that is $b + E_{\tilde{\theta}}\tilde{\theta} \geq 0$, where $E_{\tilde{\theta}}$ denotes the expectation operator over $\tilde{\theta}$, and 0 represents the return of the best alternative if the project is not developed.

Suppose that arrival of information about the future returns of the project is expected over time. Namely, at a future date, the realisation of $\tilde{\theta}$ will be known, $\tilde{\theta} = \theta$, and if the project had not been adopted yet, the project should be adopted if it is profitable, i.e. if $\theta \geq 0$. Under this scenario, viewed from today the return of the project becomes $E\max(0, \tilde{\theta})$. This implies that the optimal strategy may *not* be to adopt the project immediately despite its positive expected value.[3] The optimal strategy can be instead to wait before deciding to adopt or not the project until arrival of information and thus giving up the immediate benefit of the project b.

This shows that the prospect of receiving information in the future may lead not to developing an irreversible project even when it has a positive net present value. This is because such a project "kills" the option of taking advantage of the forthcoming information. In other words, the prospect of receiving information in the future gives a premium to the decision of not developing an irreversible project. This effect is known as the "irreversibility effect" (Henry, 1974).

Notice however that the example above is very specific. It involves perfect information, complete irreversibility, all-or-nothing decisions and risk neutrality. In the following, we will discuss conditions under which the "irreversibility effect" can be generalized. To do so, we consider from now a two-decision model represented by the following optimisation programme

$$\max_{x_1 \in D} E_{\tilde{y}} \max_{x_2 \in D(x_1)} E_{\tilde{\theta}|\tilde{y}} v(x_1, x_2, \tilde{\theta}) \tag{13}$$

The timing of the model is the following. At date 1, the decision-maker chooses x_1 in a set D. Between date 1 and date 2, he observes the realisation of a random variable, i.e. a signal, $\tilde{y}$ which is potentially correlated with $\tilde{\theta}$. At date 2, before the realisation of $\tilde{\theta}$, he chooses x_2 in a set $D(x_1)$. Finally $\tilde{\theta}$ is realised and the decision-maker has payoff $v(x_1, x_2, \theta)$. The question becomes: what is the effect of a "better information" $\tilde{y}$ on the optimal decision at date 1?[4]

Let us first answer this question using the previous example. We have $v(x_1, x_2, \theta) = x_1 b + x_2 \theta$ with $D = \{0,1\}$ and $D(x_1) = \{x_1, 1\}$. Note that the decision of

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[3] As an illustration, assume for instance $b = 1$, and that $\tilde{\theta}$ takes values +3 or -3 with equal probability. In that case, the project has a positive expected value $b + E_{\tilde{\theta}} \tilde{\theta} = 1$. But the point is that we have $E \max(0, \tilde{\theta}) = 1.5$ which is greater than 1.

[4] We note that the economic literature has used different terms to define the notion of a better information. These terms include an earlier resolution of uncertainty (Epstein, 1980), an increase in uncertainty (Jones and Ostroy, 1984), arrival of information over time (Demers, 1991), learning (Ulph and Ulph, 1997), and a better information structure (Gollier *et al.*, 2000).

developing the project, $x_1 = 1$, is irreversible in the sense that it reduces the decision set at date 2 to a singleton $D(x_1) = \{1\}$. We now compare what happens with and without information. The situation without information is equivalent to $\tilde{S}$ independent from $\tilde{\theta}$: the observation of signal $\tilde{S}$ does not give any information on the realisation of $\tilde{\theta}$. In this case, programme (13) becomes

$$\max_{x_1\in\{0,1\},x_2\in\{x_1,1\}} E_{\tilde{\theta}}(x_1 b + x_2\tilde{\theta}) = \max(b + E_{\tilde{\theta}}\tilde{\theta}, 0) \qquad (14)$$

Consider alternatively the case with (perfect) information before date 2. This is equivalent to assuming perfect correlation between $\tilde{S}$ and $\tilde{\theta}$. In this case, programme (13) becomes

$$\max_{x_1\in\{0,1\}} E_{\tilde{\theta}} \max_{x_2\in\{x_1,1\}} (x_1 b + x_2\tilde{\theta}) = \max(b + E_{\tilde{\theta}}\tilde{\theta}, E_{\tilde{\theta}}\max(0,\tilde{\theta})) \qquad (15)$$

Note that the difference between (14) and (15) corresponds to the value of perfect information. This comparison of (14) and (15) also shows that the returns of the best alternative have been re-evaluated from 0 to $V \equiv E\max(0,\tilde{\theta})$. This term V has been coined the (quasi-)option value in the literature (Arrow and Fisher, 1974). It represents the welfare-equivalent cost of investing in the irreversible project.

3.3 The effect of more information

The comparison above between (14) and (15) rests on two extreme information structures: one structure gives no information and the other gives perfect information. We now introduce the notion of "better information". This notion dates back to the mathematicians Bohnenblust, Shapley and Sherman (1949), and especially to Blackwell (1951). A convenient definition is introduced by Marschak and Miyasawa (1968). Let $\tilde{S}$ (resp. $\tilde{S}'$) an information structure potentially correlated with $\tilde{\theta}$, and π_s (resp. $\pi_{s'}$) the vector of posterior probabilities of $\tilde{\theta}$ after observing signals s (resp s'). Let also define S the set of probability distributions. Then $\tilde{S}$ is a better information structure than $\tilde{S}'$ if and only if:

$$\text{for any convex function } \rho \text{ on } S,\ E_{\tilde{s}}\rho(\pi_{\tilde{s}}) \geq E_{\tilde{s}}\rho(\pi_{\tilde{s}}) \qquad (16)$$

Thus a better information structure induces a mean-preserving spread in posterior beliefs.

We are now in a position to study the initial question about the effect of a better information structure on the optimal decision at date 1. Let us first define the value function of the second period problem as

$$j(\pi_s, x_1) = \max_{x_2 \in D(x_1)} E_{\tilde{\theta}|s} v(x_1, x_2, \tilde{\theta}) \qquad (17)$$

Note that this value function is always convex in posterior beliefs π_s since it is the maximum of linear functions of π_s. Hence from (16) any better information structure increases ex ante expected utility. This is a mathematical representation of the idea that more information is always valuable. This is always true under EU. Moreover the first order condition of problem (13) is now equal to $E_{\tilde{s}} j_1(\pi_{\tilde{s}}, x_1) = 0$ where j_1 represents the derivative of j with respect to x_1. Using (16) and (17) it is then easy to understand that better information increases the first decision if and only if $j_1(\pi_s, x_1)$ is convex in π_s. This observation about the convexity of j_1 essentially constitutes the Epstein (1980)'s theorem.

This theorem permits the investigation of the effect of better information on decisions under some regularity and differentiability assumptions,[5] and it has been extensively used in the literature. Specifically, this theorem by Epstein has been used to generalize the irreversibility effect to partial information, partial irreversibility, continuous decisions and risk aversion. To see this, assume that the second period payoff function is independent of x_1, writing for the moment

$$v(x_1, x_2, \theta) = u(x_1) + V(x_2, \theta) \qquad (18)$$

[5] Jones and Ostroy (1984) generalized Epstein's theorem to non-differentiable problems and to a more general characterization of adjustment costs.

Also assume that $D(x_1)=\left[0, f(x_1)\right]$ so that an increase in x_1 reduces the future decision set if and only if $f>0$ is decreasing. We thus can say that the irreversibility effect holds in this model if we can show that more information leads to a less irreversible decision, that is if we can show formally that j_1 is concave in the probability vector π_s whenever f is decreasing. After direct computations, it can be shown indeed that $j_1(\pi_s,x_1)=f'(x_1)\max(0,E_{\tilde{\theta}/\pi_s}V_2(f(x_1),\tilde{\theta}))$ where V_2 is the derivative of V with respect to x_2; see for instance the related results in Gollier and Treich (2003) or Mäler and Fisher (2005). Since $E_{\tilde{\theta}/\pi_s}V_2(f(x_1),\tilde{\theta})$ is linear in π_s and the maximum operator is convex, the function $\max(0,E_{\tilde{\theta}/\pi_s}V_2(f(x_1),\tilde{\theta}))$ is convex in π_s which implies that the concavity of $j_1(\pi_s,x_1)$ indeed depends on whether f' is negative. This shows that the irreversibility effect holds in general in this model.

3.4. The "precautionary effect"

In his important paper, Epstein observes that the irreversibility effect need not hold for payoff functions $v(x_1,x_2,\theta)$ in which the second period payoff directly depends on x_1, namely when (18) does not hold. Underlying this technical observation, there is a fundamental economic insight. Indeed problems related to the Precautionary Principle are usually such that the actions today affect the risks borne in the future. This implies that condition (18) typically fails. In the remainder of this subsection, we thus present (but do not prove) some results about the effect of better information in models in which $v(x_1,x_2,\theta)$ does depend on x_1. When such an intertemporal dependence is introduced, there exists a new effect that is coined the "precautionary effect". The sign of this effect is usually indeterminate and strongly depends on the functional forms considered.

A typical application of the effect of better information has been the timing of climate policy. An influential early contribution is that of Ulph and Ulph (1997) who consider a microeconomic climate change model in which the payoff function is of the form $v(x_1,x_2,\theta)=u_1(x_1)+u_2(x_2)-\theta d(\delta x_1+x_2)$. They interpret x_t as the emissions of CO2 in period t and $\theta d(.)$ as the risk of climate damage that depends on the sum of emissions up to a decay parameter δ and of the damage function $d(.)$. Observe that in that model the level of emissions today x_1 affects the climate damage borne in the future: $\theta d(\delta x_1 + x_2)$. Ulph and Ulph then show that a better information structure may well lead to increase, and not decrease, emissions at date 1. This negative precautionary effect holds in particular when the utilities and the damage function are quadratic. Similarly, Kolstad (1996) observes that the precautionary effect due to stock pollution may reverse the irreversibility effect due to investment in a pollution abatement technology. Moreover, a basic insight from Kolstad (1996) and Ulph and Ulph (1997) is that better information does have an effect on today's decisions even without the presence of an irreversibility constraint, for instance even if the set $D(x_1)$ is equal to the real line.

Gollier *et al*. (2000) analyse a model with stock effects as in Ulph and Ulph (1997) and Kolstad (1996) but with monetary damages $v(x_1, x_2, \theta) = u_1(x_1) + u_2(x_2 - \theta(\delta x_1 + x_2))$. They show that x_1 decreases with better information if and only if $u_2(.)$ has a constant relative risk aversion (CRRA) parameter lower than 1, or a derivative "sufficiently" convex. This latter condition suggests that the coefficient of prudence is instrumental for signing the effect of a better information structure on early decisions, a new insight in this literature on the effect of information. They also show an impossibility result in the sense that if the utility function u_2 does not belong to class of harmonic absolute risk aversion (HARA) utility functions, then it is not possible to sign the comparative statics analysis for all probability distributions of the risk and all information structures.

Finally, and to mention some macroeconomic applications, Epstein (1980) considers a three-period consumption model with known current return of capital R, but uncertain future return, i.e. a model of the form $v(x_1, x_2, \theta) = u_1(x_1) + u_2(x_2) + u_3(1 - R^2 x_1 - \theta x_2)$. A related model is that of Eeckhoudt, Gollier and Treich (2005) where they consider an uncertain lifetime income, namely $v(x_1, x_2, \theta) = u_1(x_1) + u_2(x_2) + u_3(\theta - R^2 x_1 - R x_2)$. These papers show that the optimal x_1 responds differently to better information depending on the curvature of the utility functions. Overall these results suggest that the qualitative effect of better information strongly depends on the functional forms, in particular on the attitude towards risk of the decision-maker.

Most papers in the last decades investigating the effect of better information have used Epstein (1980)'s theorem. This theorem is useful because the complex effect of better information characterized by all possible Blackwell-ordered information structures amounts to a study on how the properties of the value function in (17) translate into properties of the primitive model (13). One can view this theorem as a parallel of Rothshild and Stiglitz (1970)'s analysis of a change in risk to study the effect of a change in information.

We conclude this section with three remarks that concern future research. First, we observe that despite the usefulness of Epstein's theorem, it is not easy technically to translate properties on the value function onto properties on the model's primitives, and sometimes it may not even be possible to do so as shown in Gollier *et al*. (2000). Therefore there is a need to provide a complementary theorem that would directly give conditions on the model's primitives to sign the effect of better information. Second, it would be interesting to consider the comparative static analysis of better information with a less general notion than that of Blackwell. While alternative notions like monotone likelihood ratios have been used in the static value of information literature, we have not seen yet the use of these notions in sequential option value models. Third, we notice that virtually all the literature relies on the use of the (Savagian) expected utility framework, and it does not seem obvious to study the effect of better information in broader or different frameworks. One typical difficulty is that alternative frameworks may induce a negative value of information. This last remark relates to the literature on ambiguity and ambiguity aversion that we briefly discuss now.

3.5. Ambiguity aversion

It turns out that there is another approach to precaution. This approach is based on models involving ambiguity (aversion), i.e. models that can accommodate the Ellsberg (1961)'s paradox like for instance the early maxmin model of Gilboa and Schmeidler (1989) or the recent smooth ambiguity aversion model of Klibanoff *et al*. (2005). As precaution usually refers to situations in which there is ambiguity over probability distributions, many scholars actually believe that ambiguity (aversion) provides a more natural approach to study issues related to the Precautionary Principle. This approach also proposes a fairly simple distinction between risk and uncertainty. Risk corresponds to a situation in which the decision-maker believes that there is a unique probability distribution while uncertainty (i.e. ambiguity) corresponds to a situation in which he believes that there are multiple coexisting probability distributions.

To illustrate, we use the recent Klibanoff *et al*. (2005)'s theory of ambiguity (aversion) and apply it to the basic self-insurance model introduced in equation (1). But assume there might be multiple probabilities of loss denoted now by the random variable $\tilde{p}$. Formally, the objective function then becomes

$$V(y) = \Phi^{-1}\left[E_{\tilde{p}}\Phi\left[\tilde{p}u(w_0 - c(y) - L(y)) + (1-\tilde{p})u(w_0 - c(y))\right]\right] \tag{19}$$

in which a concave (resp. convex) function $\Phi[.]$ represents ambiguity aversion (resp. ambiguity loving); see Klibanoff *et al*. (2005) for a representation theorem of this model. The function $\Phi[.]$ captures the gain in utility associated with a mean-preserving contraction in $\tilde{p}$. At the limit, when $\tilde{p}$ is degenerate and equal to p_0 with probability 1, we are back to the model defined by equation (1). In that case, there is no ambiguity over probabilities, we are in a risk situation and ambiguity aversion naturally plays no role. Observe alternatively that under ambiguity neutrality, i.e. under $\Phi[.]$ linear, we are also back to the EU model of equation (1) under $E_{\tilde{p}}\tilde{p} = p_0$ despite the presence of ambiguity.

Interestingly, Treich (2010) and Snow (2011) studied the effects of the presence of ambiguity and of ambiguity aversion on self-insurance and self-protection choices. Treich (2010) showed that ambiguity aversion increases the VSL as soon as the marginal utility of wealth is higher if alive and dead. Snow (2011) showed that the levels of self-insurance and self-protection activities that are optimal for an ambiguity-averse decision maker are higher in the presence of ambiguity than in its absence, and always increase with greater ambiguity aversion.

A major concern however is that ambiguity (aversion) models have long been criticized for introducing anomalies in dynamic settings. Al-Najjar and Weinstein (2010) recently summarize these criticisms. In particular, they emphasize that it is not clear how to update beliefs in ambiguity (aversion) models. They also show that these models systematically induce time-inconsistent choices. As we initially argued that precaution is fundamentally a dynamic concept, we therefore believe that it is perhaps premature to include a thorough discussion of ambiguity models in this section on precaution. But we also believe this is probably the most promising avenue of research in this area.

4. Conclusion

Prevention is one tool amongst others to manage risks. Yet, it differs from others in the sense that it alters the risk itself via a modification either of the loss probability or the consequences of the risk. This chapter has shown that in the last 40 years the economic literature on prevention has been developed in many directions. Most significantly, these directions include the analysis of: (i) the specificities and complementarities between self-insurance, self-protection and insurance choices, (ii) the effect of wealth, risk preferences (e.g. risk aversion, prudence) and different risks (e.g. background risks, non-monetary risks) on these choices, and (iii) prevention under alternative decision theoretic frameworks to EU known as non-EU models.

All in all, it seems that this research area has undergone significant developments similar to other research areas within the economics of risk, uncertainty and insurance, like for instance the theoretic analysis of portfolio choices and insurance demand. Nevertheless, in comparison to other areas, the empirical literature on prevention is quite thin. For instance, we are not aware of any important empirical "puzzle" in the literature on prevention similar to the "equity premium puzzle" that could have a stimulating effect on the production of empirical papers.

It is worth mentioning that prevention is also studied in other fields of economics than the economics of risk, uncertainty and insurance. For instance, there exists various works on self-protection in the literature of game theory. These works make reference to the concepts of contest and rent seeking (see Congleton *et al.*, 2010). There also exists a literature on incentives to invest in prevention with respect to liability rules in the analysis of law economics as well as in the literature of the economics of crime (see Kaplow and Shavell, 2002). Lastly, in public economics, prevention is analysed in terms of public goods versus private goods (see Shogren and Crocker, 1991, 1998; Quiggin 1998).

This chapter has also discussed the difference between prevention and precaution. Prevention can be viewed as a static concept that refers to the management of a risk at a given time and given a stable probability distribution. In contrast, precaution is a dynamic concept related to the management of uncertainty that recognizes that there is scientific progress over time. In that sense, the crucial question underlying the literature on precaution is how the prospect of receiving information in the future affects today's decisions. This is why the concept of precaution is strongly linked to the study of sequential models with arrival of information over time. An alternative approach to precaution is to consider situations in which there is ambiguity over probability distributions. Hence, a future research challenge would be to combine both approaches, that is to perform a sequential analysis in models of ambiguity (aversion).

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