Innovation and information acquisition under time inconsistency and uncertainty

Sophie Chemarin, Caroline Orset

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Abstract

This paper analyzes the impact of hyperbolic discounting preferences on the agent's information acquisition decision who wants to undertake a potential dangerous activity for human health or the environment. We find that below certain discount rate threshold, an agent prefers ignoring information and continuing his project. On the other hand, above this threshold, it is optimal for him to acquire information, and the investment for acquiring the information is increasing with the discount rate. We then conclude that hyperbolic discounting preferences limit the information acquisition. Moreover, we explain that the lack of self-control induced by hyperbolic discounting preferences also restraints the information acquisition. Finally, we analyze the efficiency of the strict liability rule and the negligence rule to motivate the agent to acquire information.

Keywords: innovation, information acquisition, uncertainty, self-control, time inconsistency, liability rules.

JEL Classification: D81, D83, D92.

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Introduction

A recent report of the European Commission (Aho, 2006) emphasizes the large gap between the scientific and technological knowledge of European countries and the relatively low level of innovation. Actually, the non-stability and/or the lack of information characterizing innovations constitute one of the main barriers to innovation. As an example of scientific innovation, one could point out genetically modified organisms (GMO)([29]). The general principle of producing GMO is to add genetic material into an organism's genome to generate new traits. Examples of GMOs are highly diverse several fish species, transgenic plants (e.g. tomatoes), medicines (e.g. gene therapy), or agricultural products (e.g. golden rice). As for many innovations, we do not perfectly know the effects that GMOs may entail on people's health and/or on the environment. The recent debate on the toxicity of transgenic maize plants MON863 emphasizes the difficulties to define what should be the adequate and proportionate decision to take under such a context of scientific uncertainty. If recent scientific studies seem to point out a potential danger due to the consumption of this kind of transgenic plants, maize MON863 is not forbidden in France while it is, for example, in Netherlands (Seralini, Cellier and Spiroux de Vendomoix, 2007). Indeed, the French "Commission du Génie biomoléculaire" (CGB) concludes in their experts report that *"the results of the toxicological study did not point out any toxic effects on rats kidney due to the consumption of maize 863"* (CGB, June 15th 2007). In such a context, should we limit technological and scientific innovation as it is done regarding GMOs production in California (United States) or in Prince Edward Island (Canada), which ban all of them to prevent a possible risk? On the other hand, would not it be more relevant to encourage innovation's and research's efforts at the same time in order to reduce scientific uncertainties and to behave according to the information they could obtain from it?

The European report on innovation concludes that there is a real need for action to implement what it defines as a *"pact for research and innovation"* (Aho, 2006). Indeed, investing in research and development allows a reduction of the scientific uncertainty which characterizes the innovations. In this regard, the precautionary principle, as a public decision criteria, proposes to combine innovation, security and information acquisition (Pouillard, 1999, Henry and Henry, 2004). It inspires many European directives and propositions that aim at protecting health and environment. Thus, the directive on environmental liability proposes to apply the 'pollutant-payer' principle: if a damage happens, the pollutant has to pay for it. The investors are then liable for eventual incident due to their activities. The goal of this principle is to act directly on the investors behaviours to increase their prevention and research efforts. Mechanisms based on liability rules, such as a strict liability rule (which use is in the spirit of the application of the precautionary principle) or a negligence rule, are used to protect consumers as well as the environment by improving the control and the prevention of risks induced by firms' activities and products. However, uncertainty limits their efficiency but also induces contradictory effects on both innovation and security. For example, regarding technological risks, Sinclair-Desgagné and Vachon (1999) note that limited liability leads to less prevention and the extension of the liability to all the firm's partners may limit innovating efforts. To go further in the current debate on precaution and economic development, one should investigate what determines, under existing liability framework, the innovation decision of an investor regarding activities for which scientific knowledge is still incomplete.

Individual risks perception and thus risks assessment is never exempt of subjectivity. For example, according to Kahneman, Slovic and Tversky (1982), people undervalue or overvalue small probabilities in proportion to the importance of potential damages, and according to their past experiences. In a more general way, as emphasized by several empirical studies, risk perception and thus, individual preferences change over time (Frederick, Loewenstein and O'Donoghue, 2002). Strotz (1956) is the first to suggest an alternative to exponential discounting. Phelps and Pollack (1968) introduce the functional form of this kind of changing preferences. Let $D(k)$ represent a discount function such that:

$$\begin{cases} D(k) = 1 & \text{if } k = 0; \\ D(k) = \beta\delta^k & \text{if } k > 0. \end{cases}$$

We can define a hyperbolic discounted utility function as follows:

$$U_t = \sum_{k=0}^{T-t} D(k) u_k.$$

Elster (1979) applies this (β, δ) formalization to a decision problem in characterizing time inconsistency by a decreasing discount rate between the present and the future and a constant discount rate between two future periods. Laibson (1997, 1998) then uses this formulation to saving and consumption problems, while other economists like Bénabou, Tirole (2002, 2004) and Carrillo, Mariotti (2000) apply it into the problem of information acquisition. In particular, Carrillo and Mariotti (2000) describe intertemporal consumption's decisions involving a potential risk in the long run. They show that hyperbolic discounting can favour *strategic ignorance*. Indeed, a person with time inconsistent preferences might choose not to acquire free information in order to avoid over consumption or engagement in activities, which may require much more fundamental research on potential social costs or externalities they could involve in the long term. However, if ignorance

is a self-disciplining device when an agent is confronted to uncertainty and hyperbolic discounting, is it then useless for him to acquire information to develop a project?
In this paper, we propose to analyze the impact of hyperbolic discounting preferences on the agent's information acquisition decision who wants to undertake a activities with potential risks on health or the environment. We choose to both define information acquisition as an investment in research[1] to reduce the uncertainty on the potential risk of damage, and to study innovator's intertemporal choices as a joint product of many conflicting psychological motives. Since empirical studies (Frederick and al., 2002) suggest it, the innovator's preferences are described by a hyperbolic discounting function. In such a case, preferences are said to be *time inconsistent*. The discount rate β gathers, as in Akerlof (1991) and Carrillo and Mariotti (2000), all the psychological motives of the agent's investment choice such that anxiety, confidence or impatience. If $\beta = 1$, the psychological motives have no influence on his choice, and his preferences are time consistent. On the other hand, if $\beta < 1$, the innovator is temporally inconsistent.

Under uncertainty, we first study the optimal decision-making of an innovator with hyperbolic discounting preferences. This allows us to analyze the direct impact of the hyperbolic preferences on the information acquisition decision. We then study the lack of self-control induced by the hyperbolic discounting preferences on the acquisition information. In this regard, we define the self-control effect as the agent's ability to commit in the future. Finally, we study how two main forms of liability - strict liability and negligence rule - may give incentives the innovator to acquire information. We choose to provide the investment in research (i.e. information acquisition) as a measure of care, in so far as it leads to a reduction of the uncertainty linked to the innovation, and to decisions that may reduce the cost of damages suffered by both the innovator (according to the liability rule enforced) and the environment in case of accident.

As a result, we show that below a certain discount rate threshold, acquiring information is not optimal. The innovator prefers ignoring information in order to never stop his project and to protect his innovation's ability. On the other hand, above this threshold, the investment in research is increasing with the value of β. We then conclude that the hyperbolic discounting preferences limit the information acquisition and favours the strategic ignorance. Moreover, we explain that the lack of self-control induced by hyperbolic discounting preferences also favours the strategic ignorance. Finally, because such ignorance behaviours have to be regulated to both protect people and environment, we

[1] Such investment in research could be considered as a resort to private experts like private laboratory or to any other private party able to provide scientific knowledge on the dangerousness or more generally on the characteristics on the innovator's activities

show that, due to the hyperbolic discounting preferences and uncertainty, the impacts of liability rules on the innovator's ability to acquire information is not so clear. Indeed, hyperbolic discounting preferences limit the efficiency of the strict liability rule to motivate the agent to acquire information. Nevertheless, we show that the negligence rule may be an alternative tool to avoid the hyperbolic discounting preferences effect and then may incentive the agent to acquire information.

The paper is organized as follows. Section 1 presents the model. Section 2 investigates the optimal decision-making. Section 3 studies the self-control effect. Finally, section 4 proposes solutions, the strict liability and the negligence rule, to incentive the innovator to acquire information. All proofs are in appendix.

1 The model

We consider a three periods model. At period 0, the innovator invests a given amount of money I in a project that may create damage on the environment or on people health.

There are two possible states of the world: a dangerous state noted H and a less dangerous state, L. The probability that a damage happens is θ^H in state H and θ^L in state L. Since H is the most dangerous state of the world, we obtain

$$\theta^L < \theta^H.$$

At the beginning, the prior beliefs of the innovator are p_0 on the state H and $1 - p_0$ on the state L. We then define the expected probability of the damage by

$$E(\theta) = p_0\theta^H + (1 - p_0)\theta^L.$$

At period 0, the innovator invests $C \geq 0$ in research, to obtain information at period 1, through a signal $\sigma \in \{h, l\}$ on the true state of the world. We define the precision of the signal as an increasing and concave function $f(C)$ such that:

$$P(h|H, C) = P(l|L, C) = f(C) \text{ and } P(h|L, C) = P(l|H, C) = 1 - f(C)$$

and

$$f(0) = \tfrac{1}{2};\ f'(0) = +\infty \text{ and } f'(+\infty) = 0.$$

Hence, the signal is not informative when the innovator does not invest in research and it becomes more and more precise, i.e. $P(h|H, C)$ increases and $P(l|L, C)$ decreases when C increases.

According to Bayes' rule,

$$P(h|H,C) = \frac{p_0 f(C)}{p_0 f(C) + (1-p_0)(1-f(C))} \quad \text{and} \quad P(H|l,C) = \frac{p_0(1-f(C))}{p_0(1-f(C)) + (1-p_0)f(C)}.$$

At period 1, according to the perceived signal the innovator decides to stop his project with a probability $1-x$, or to continue it with a probability x, with $x = x_\sigma$ for signal $\sigma \in \{l, h\}$. If the innovator stops the project, he recovers a part of his investment D such that $0 < D < I$. Nevertheless, if he decides completely to achieve it, he wil receive a positive return R_2 at the next period (period 2).

An accident may occur at period 2. If it occurs while the innovator has prematurely stopped his project, he suffers a financial cost K' related to the damages. But if it occurs while he has decided to complete the project, the financial cost K is higher. So, we assume

$$0 < K' < K.$$

We define by B^S the undiscounted benefit to continue the project instead of stopping it at period 1, when the state of nature is $S \in \{L, H\}$, i.e.

$$B^S = (R_2 - \theta^S K) - (D - \theta^S K').$$

We assume that the undiscounted benefit is positive in state L while it is negative in state H so

$$B^H < 0 < B^L.$$

A collection of risk-neutral incarnations with conflicting goals represents the innovator's preferences.[2] At each period t, there is only one incarnation called "self-t". Each self-t depreciates the following period with a discount rate $\beta < 1$.[3] In our model, we consider that β represents the salience of current payoffs relative to the future stream of returns. Remember our GMOs farmer's example, his confidence with GMOs may decrease over time because of a better knowledge of their potential negative effects (i.e. reduction of the scientific uncertainty), which could imply period-to-period different decisions.

Hence, intertemporal expected payoffs of self-t$= 0, 1, 2$ may be expressed recursively. If signal σ has been perceived, self-2's intertemporal expected payoff is written as

$$\begin{aligned} V_2(x_\sigma, \sigma, C) = \ & x_\sigma[P(H|\sigma,C)(R_2 - \theta^H K) + (1 - P(H|\sigma,C))(R_2 - \theta^L K)] \\ & -(1-x_\sigma)[P(H|\sigma,C)\theta^H K' + (1 - P(H|\sigma,C))\theta^L K']. \end{aligned}$$

[2]Following Strotz (1956), this conflict is captured by assuming that the innovator's preferences are dynamically inconsistent.

[3]Akerlof (1991) defines β as the *"salience of current payoffs relative to the future stream of returns"*, but it is also interpreted in the literature as a lack of willpower (Bénabou and Tirole, 2002), of foresight (Masson (2002), O'Donoghue and Rabin (1999)) or as impatience or impulsiveness (Ainslie, 1992). Moreover, to simplify the (β, δ) formalization, we assume that $\delta = 1$.

Likewise, self-1's intertemporal expected payoff is

$$V_1(x_\sigma,\sigma,C) = (1-x_\sigma)D + \beta V_2(x_\sigma,\sigma,C).$$

Finally, self-0's intertemporal expected payoff is

$$\begin{aligned} V_0(x_h,x_l,C) = \quad & -I - C + \beta[p_0 f(C) + (1-p_0)(1-f(C))](V_2(x_h,h,C) + (1-x_h)D) \\ & +\beta[(1-p_0)f(C) + p_0(1-f(C))](V_2(x_l,l,C) + (1-x_l)D). \end{aligned}$$

We define $\widehat{\theta}(\beta)$ as the damage probability threshold for which self-1 is indifferent between stopping or carrying on the project to the end. Since $\widehat{\theta}(\beta)$ is such that $D - \beta K' = \beta(R_2 - K)$, we obtain

$$\widehat{\theta}(\beta) = \frac{\beta R_2 - D}{\beta(K-K')}.$$

We also assume that

$$E(\theta) \leq \widehat{\theta}(\beta) \text{ which is equivalent to } \beta R_2 - \beta E(\theta)K \geq D - \beta E(\theta)K'. \tag{1}$$

Hence, if no research effort is made ($C = 0$), i.e. with No Learning, self-1 continues the project to the end.

So, self-0's expected payoff with No Learning is written as

$$\begin{aligned} V_0^{NL}(\beta) & = -I + \beta[p_0(R_2 - \theta^H K) + (1-p_0)(R_2 - \theta^L K)]. \\ & = -I + \beta[R_2 - E(\theta)K]. \end{aligned}$$

2 The optimal decision-making

We now turn to the innovator's optimal decision-making. Subsection 2.1 studies self-1's optimal decision to continue the project or to stop it, and subsection 2.2 determines self-0's optimal decision to acquire information.

2.1 Stopping or continuing the project

At period 1, if self-1 is uninformed he always continues his project. However, if he gets information, he receives a signal $\sigma \in \{h,l\}$ on the probability of damage and updates his beliefs. According to this information, he has to choose either to complete or not his project. Formally, for $\sigma \in \{h,l\}$ and for all $C \geq 0$, self-1 continues the project if his expected payoff when he continues the project is higher than when he stops it, i.e.

$$V_1(1,\sigma,C) \geq V_1(0,\sigma,C).$$

After signal $\sigma \in h,l$ has been perceived, let $E(\theta|\sigma,C) = P(H|\sigma,C)\theta^H + (1-P(H|\sigma,C))\theta^L$ be the expected probability of a damage and x^*_σ the equilibrium strategy.

Proposition 1 *If $E(\theta|\sigma, C) \leq \widehat{\theta}(\beta)$, then $x^*_\sigma = 1$: the innovator continues the project; if $\widehat{\theta}(\beta) < E(\theta|\sigma, C)$, then $x^*_\sigma = 0$: the innovator stops the project.*

Proposition 1 characterizes the conditions on the revised expected probability of the damage, $E(\theta|\sigma, C)$, under which self-1 decides to partially or completely achieve his project. These two cases may arise. If $E(\theta|\sigma, C)$ is lower (resp. larger) than the threshold $\widehat{\theta}(\beta)$, self-1's optimal decision is to carry on (resp. to stop) the project.

We easily verify that $\widehat{\theta}(\beta)$ is increasing with β:

$$\widehat{\theta}'(\beta) = \frac{D}{\beta^2(K - K')}$$

is positive. So, for all $\beta \in]0, 1]$,

$$\widehat{\theta}(\beta) \leq \widehat{\theta}(1).$$

So according to Proposition 1, the range of values in which the hyperbolic agent ($\beta < 1$) may decide to stop his project at period 1 is higher than the one of the exponential agent ($\beta = 1$), also defined as an innovator with consistent preferences.

Lemma 1 *$E(\theta|l, C) \leq E(\theta) \leq E(\theta|h, C)$ for all $C \geq 0$. And $E(\theta|h, C)$ is increasing with C while $E(\theta|l, C)$ is decreasing with C.*

Then the second part of Lemma 1 suggests that from a certain value of C, the signal have an impact on the decision.

Moreover, according to Lemma 1 and condition (1), when self-1 receives signal l, he always decides to continue the project while when he receives signal h, if $\widehat{\theta}(\beta)$ is higher (lower) than $E(\theta|h, C)$ self-1 continues (stops) his project.

Overall, two possible cases may occur: either self-1 always continues the project whatever the signal, or self-1 behaves according to the information he gets and continues (stops) the project if he receives signal l (h).

2.2 Information acquisition

At period 0, self-0 chooses his optimal research investment $C^*(\beta)$ to acquire information on the risk of accident, knowing that at period 1, self-1 either always continues the project whatever the signal (case 1) or stops (continues) it if he received the signal h (l) (case 2). However, self-0 has no commitment power, he then cannot control the future self's decision.

We first study case 1, i.e. self-1 always continues the project. Self-0's expected payoff is

$$V_0(1,1,C) = -I - C + \beta[p_0(R_2 - \theta^H K) + (1-p_0)(R_2 - \theta^L K)].$$

Since $V_0(1,1,C)$ is decreasing with C, among all the possible levels of investment, it is obvious that the optimal solution is

$$C^*_{11}(\beta) = 0.$$

Since, the signal does not have any influence on self-1's behaviour (i.e. whatever the signal self-1 continues the project), it is then not surprising that optimally at period 0, self-0 does not want to invest in research and then does not acquire any information. Overall, optimally case 1 is equivalent to the situation where the innovator is uninformed.

We now turn to case 2. Self-1 stops (continues) the project according to the signal he receives. Self-0's expected payoff is

$$\begin{aligned} V_0(0,1,C) = \quad & -I - C + \beta[p_0(1-f(C))(R_2 - \theta^H K) + (1-p_0)f(C)(R_2 - \theta^L K)] \\ & +\beta[p_0 f(C)(D - \theta^H K') + (1-p_0)(1-f(C))(D - \theta^L K')]. \end{aligned}$$

Define by $C_{01}(\beta)$ the investment in research which solves the following problem

$$\max_{C \geq 0} V_0(0,1,C). \tag{2}$$

We get:

Proposition 2 $C_{01}(\beta)$ *is characterized by*

$$f'(C_{01}(\beta)) = \frac{1}{\beta[(1-p_0)B^L - p_0 B^H]}. \tag{3}$$

$C_{01}(\beta)$ *is increasing with* β.

However, in this case the investment in research chosen by self-0 leads self-1 to choose the strategy $[x^*_l = 1, x^*_h = 0]$. We then define by $\widehat{C}(\beta)$ the smallest $C \geq 0$ which satisfies the following condition

$$E(\theta|l,C) \leq \widehat{\theta}(\beta) \leq E(\theta|h,C).$$

Proposition 3 $\widehat{C}(\beta)$ *is characterized by*

$$f(\widehat{C}(\beta)) = \frac{p_0(\theta^H - \widehat{\theta}(\beta))}{p_0(\theta^H - \widehat{\theta}(\beta)) + (1-p_0)(\widehat{\theta}(\beta) - \theta^L)}.$$

$\widehat{C}$ *is decreasing with* β.

Finally, to define the optimal investment in information $C^*_{01}(\beta)$ that provides useful information (i.e. a signal that influence self-1's decision), self-0 has to solve the following expected payoff maximization problem

$$\begin{cases} \max_C V_0(0,1,C) \\ \widehat{C}(\beta) \leq C. \end{cases}$$

Proposition 4 characterizes self-0 's optimal investment in research $C^*_{01}(\beta)$ under the assumption that self-1 behaves according to $[x^*_l = 1, x^*_h = 0]$ strategy.

Proposition 4 *There exists a unique* $\overline{\beta} \in]0,1]$ *such that* $C_{01}(\overline{\beta}) = \widehat{C}(\overline{\beta})$ *and for all* $\beta \in [0,\overline{\beta}]$ *then* $C^*_{01}(\beta) = \widehat{C}(\beta)$*; for all* $\beta \in]\overline{\beta},1]$ *then* $C^*_{01}(\beta) = C_{01}(\beta)$.

We note that $\overline{\beta} \neq 0$. Indeed, if we suppose that $\overline{\beta} = 0$ then:

- $f'(C_{01}(0)) = +\infty$ and since f is concave, $C_{01}(0) = 0$;
- $f(\widehat{C}(0)) = \frac{p_0}{2p_0-1}$.

If $C_{01}(0) = \widehat{C}(0) = 0$ then $f(0) = \frac{p_0}{2p_0-1} = \frac{1}{2}$ which is impossible because $-1 \neq 0$.

Although self-0 invests in research and self-1 behaves according to the information he gets, one should underline that the level of this investment depends on the discount value β.

We define by $C^*(\beta)$ the optimal research investment. To find $C^*(\beta)$, we compare the self-0's expected payoff of both strategies and we select the level of research investment that leads, from self-0's perspective, to the highest expected payoff. This gives the following proposition.

Proposition 5 *The optimal research investment* $C^*(\beta)$ *is such that for all* $\beta \in [0,\overline{\beta}]$ *then* $C^*(\beta) = 0$*; for all* $\beta \in]\overline{\beta},1]$ *then* $C^*(\beta) = C_{01}(\beta)$.

Figure 1 illustrates Proposition 5. To obtain the shape of the function $C_{01}(\beta)$, we first differentiate equation (3) with respect to β, we obtain:

$$f''(C_{01}(\beta))C'_{01}(\beta) = \frac{-1}{\beta^2[(1-p_0)B^L - p_0 B^H]}.$$

And then since f is concave, when β tends towards infinity $C'_{01}(\beta)$ tends towards infinity and when β tends towards zero $C'_{01}(\beta)$ tends towards zero. So, we get the following figure:

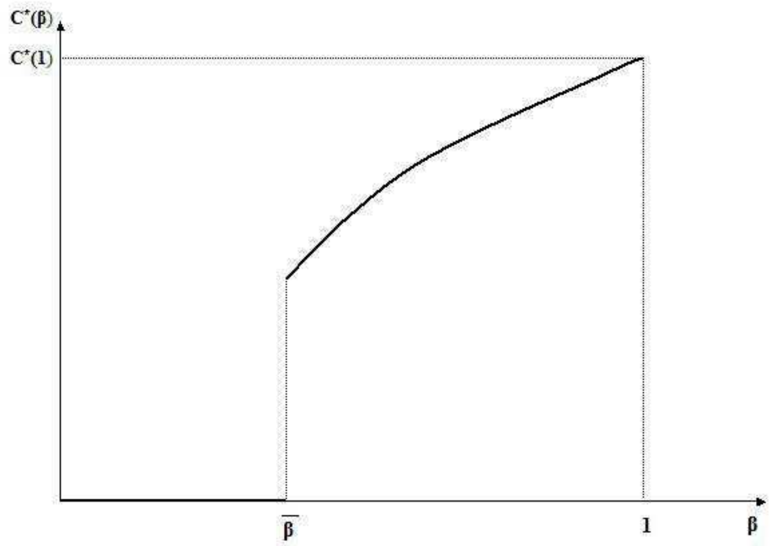

Figure 1: Optimal research investment.

Parameter β gathers the set of innovator's psychological factors. It is then not surprising that β influences the innovator's behaviour. For $\beta \in [0, \overline{\beta}]$, it is not optimal for the innovator to invest in research. He refuses to acquire information on the probability damage and keeps innovating. Actually, for $\beta \in [0, \overline{\beta}]$, the innovator has a strong preference for the present. He prefers earning money now than waiting for future payoff. If he gets information, he has the choice between stopping his project now and recovering a part of his investment and continuing his project and waiting for return payoff. So his preference for the present may lead him to stop prematurely his project. To avoid stopping the project, the innovator may prefer not obtaining information and always continuing.

On the other hand, for $\beta \in]\overline{\beta}, 1]$, the optimal investment in information is increasing with β. It tends toward the optimal investment reached when the agent has time consistent preferences and a commitment power (i.e. $C^*(1)$).

Moreover, we note a discontinuity for the optimal research investment function $C^*(\beta)$. Actually, since the information precision is increasing with the research investment, the research investment must be rather large so that the information precision is valuable for the agent and he then decides to invest in research.

According to Proposition 5, the exponential agent ($\beta = 1$) always invests in research and his investment is $C^*_{01}(1)$. On the other hand, the hyperbolic agent ($\beta < 1$) only gets information when $\beta \in]\overline{\beta}, 1]$.

Hence, Result 1 may arise:

Result 1 *The hyperbolic discounting effect limits the information acquisition.*

This result fits into the literature on hyperbolic discounting. Akerlof (1991) points out that a time inconsistent innovator ($\beta < 1$) always postpones a costly activity (or investment). In our model since the innovator has only the choice to invest in research at period 0, postponing this investment is equivalent to not doing it.

Now, we may take a look on Figure 2. For $\beta \in [0, \overline{\beta}]$, a low investment in research has no influence on self-1's behaviour, the information precision is not large enough. Indeed, for all $C \geq 0$, $V_0(1, 1, 0) > V_0(0, 1, C)$. The investor has strong preferences for the present and do not really care about what can happen in the future, there is no value of C that makes him change his behaviour. On the other hand, for $\beta \in]\overline{\beta}, 1]$, $V_0(0, 1, C^*_{01}(\beta)) > V_0(1, 1, 0)$ and $C^*_{01}(\beta)$ gives a valuable information to self-1.

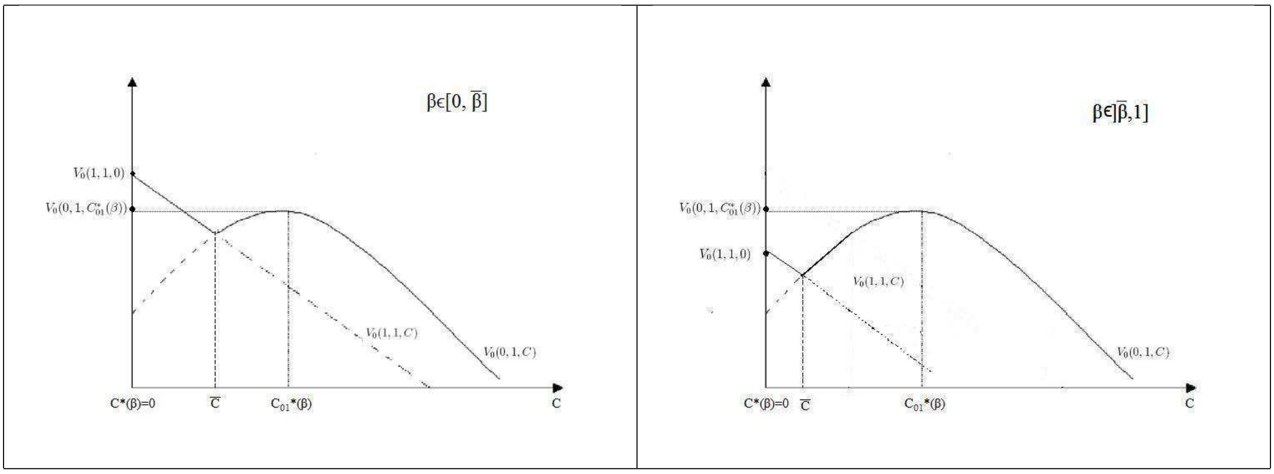

Figure 2: Optimal research investment with $\beta \in [0, \overline{\beta}]$ and $\beta \in]\overline{\beta}, 1]$.

We make a last remark. If there is no recovered investment D or if D is given at period 2, the selves 1 with $\beta = 1$ and with $\beta < 1$ have the same condition to stop or not their project. Actually, since a hyperbolic innovator ($\beta < 1$) much prefers earning money now than tomorrow, when D is given at period 1, he has more incentive than the exponential innovator to obtain D now, and to stop the project, than to wait for future gains.

3 The effect of self-control

According to Salanié and Treich (2006), a self-control effect is induced by the hyperbolic discounting preferences. The self-control effect may be defined as the agents ability to commit in the future. Hence, a lack of self-control implies that there is no possibility of commitment between the future selves of the innovator (i.e. $\beta < 1$ between the period 1 and the period 2). On the other hand, self-control leads to a commitment power (i.e. $\beta = 1$ between the period 1 and the period 2). Such effect does not depend on whether the innovator's preferences display a 'bias for the present' or not, it is then not straightforward that a lack of self-control leads to less research investment.

Self-control problems characterized situations where investors may have difficulties to undertake long run strategies. For example, the development of chemicals or medicines might suffer from a possible lack of commitment power. If the research and development stage concerning a new drug is only realized at the time when the firm invests in this new product, the decision to develop it is taken according to the information provided by the R& D stage. Since there is no others information available in the future, there is no reason for the firm to modify her decision. In others words, as soon as the decision is taken according to the ex-ante available information, there is self-control. In contrast, if there is a stock of information available during all the periods of the new product development, it is difficult to implement a strategy in the long run, without modifying this strategy according to the information. In such a case, since the firm might not be able to commit in the long run, there might be a lack of self-control.

According to Salanié and Treich (2006), to analyze the self-control effect on the innovator's behaviour, we isolate it in comparing the decision of an innovator with a lack of self-control (see previous section),[4] to the decision of an innovator with self-control.

The innovator with self-control follows the same timing of the intra-personal game. His intertemporal payoffs are similar to those of an innovator with a lack of self-control. We only switch $\beta < 1$ to $\beta = 1$ between periods 1 and 2.

We define x^{**}_{σ} the equilibrium strategy after signal σ has been perceived. Thus, we immediately obtain:

[4] We already studied the behaviour of an innovator with a lack of self-control in the previous section which analyzes the impact of the discounting effect on the investor's decision to invest in research.

Lemma 2 *For all $\sigma \in \{h, l\}$, if $E(\theta|\sigma, C) < \widehat{\theta}(1)$, then $x_\sigma^{**} = 1$: the innovator continues the project; if $\widehat{\theta}(1) < E(\theta|\sigma, C)$, then $x_\sigma^{**} = 0$: the innovator stops the project.*

Lemma 2 characterizes the conditions on the expected probability of the damage according to the signal, $E(\theta|\sigma, C)$, under which self-1 with self-control stops or carries on his project.

According to Lemma 1 and condition (1), we obtain two cases again. Self-1 always continues the project whatever the received signal; or self-1 continues (stops) the project if he receives the signal l (h).

Self-0 gets the same intertemporal payoff than the one of an innovator with a lack of self-control. Only the damage probability threshold that condition self-1's decision changes: $\widehat{\theta}(\beta)$ is switching in $\widehat{\theta}(1)$. We define $C^{**}(\beta)$ the optimal research investment for an innovator with self-control. We then obtain:

Lemma 3 *There exists $\overline{\overline{\beta}} \in [0, 1]$ such that $C_{01}(\overline{\overline{\beta}}) = \widehat{C}(1)$. Then $C^{**}(\beta)$ is such that for all $\beta \in [0, \overline{\overline{\beta}}]$ then $C^{**}(\beta) = 0$; for all $\beta \in]\overline{\overline{\beta}}, 1]$ then $C^{**}(\beta) = C_{01}(\beta)$.*

We note that $\overline{\overline{\beta}}$ may be equal to zero. Indeed, if $\overline{\overline{\beta}} = 0$ then $f'(C_{01}(0)) = +\infty$. Since f is concave that implies $C_{01}(\beta) = 0$. If $C_{01}(0) = \widehat{C}(1) = 0$, we obtain that $f(0) = \frac{p_0(\theta^H - \widehat{\theta}(1))}{p_0(\theta^H - \widehat{\theta}(1)) + (1-p_0)(\widehat{\theta}(1) - \theta^L)} = \frac{1}{2}$. Thus, $E(\theta) = \widehat{\theta}(1)$ which is impossible by assumption.

It is then not surprising that β influences the innovator's behaviour again. For low value of β, the innovator ignores the information and continues the project. Nevertheless, for high values of β, linking innovation and information acquisition seems possible.

We turn now to the self-control effect and compare the behaviour of the innovator with a lack of self-control to the behaviour of the innovator with self-control.

First, according to Proposition 1 and Lemma 3 when the self-0 gets information, the innovator with self-control has more opportunity to achieve the project than the innovator with a lack of self-control.

Moreover, according to Proposition 5 and Lemma 3, the innovator with a lack of self-control (respectively with self-control) does not invest in research when $\beta \leq \overline{\beta}$ (respectively. $\beta \leq \overline{\overline{\beta}}$) and starts investing after this threshold. $\overline{\beta}$ and $\overline{\overline{\beta}}$ are respectively characterized by $C_{01}(\overline{\beta}) = \widehat{C}(\overline{\beta})$ and $C_{01}(\overline{\overline{\beta}}) = \widehat{C}(1)$. We then obtain:

Lemma 4 $\overline{\overline{\beta}} < \overline{\beta}$.

So, according to Proposition 5 and Lemmas 3 and 4, we obtain that:

- If $\beta \in [0, \overline{\overline{\beta}}]$, then $C^*(\beta) = C^{**}(\beta) = 0$;
- if $\beta \in]\overline{\overline{\beta}}, \overline{\beta}]$, then $C^*(\beta) = 0$ and $C^{**}(\beta) = C^*_{01}(\beta)$;
- if $\beta \in]\overline{\beta}, 1]$, then $C^*(\beta) = C^{**}(\beta) = C^*_{01}(\beta)$.

Figure 3 illustrates this result.

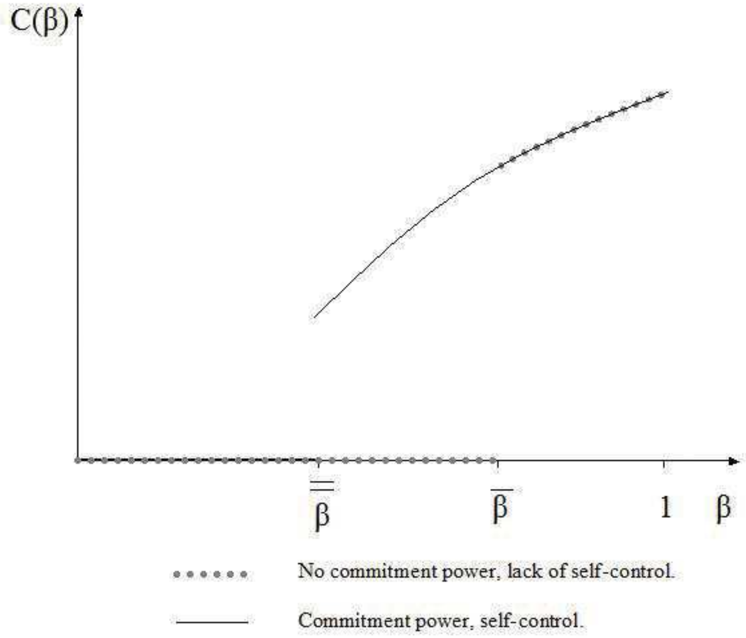

Figure 3: The effect of self-control on the investment in research.

When $\beta \in [0, \overline{\overline{\beta}}]$, both innovators (i.e. with self control and with a lack of self-control) prefer ignoring the information on the probability of damage because they strongly discount the cost of damage. But, when $\beta \in]\overline{\overline{\beta}}, \overline{\beta}]$, the innovator with self-control starts investing in research to acquire information, while the innovator with a lack of self-control prefers staying ignorant. Finally, when $\beta \in]\overline{\beta}, 1]$ both types of innovators acquire information and choose the same research investment level. As a result, we finally obtain:

Result 2 *The self-control effect limits the information acquisition.*

Moreover, we again point out that if there is no recovered investment D, or if D is given at period 2, there is no self-control effect.[5]

4 Solutions to incentive the information acquisition

Firms are constrained by a legal framework, in which liability rules specify how to allocate damages from an accident. Regarding innovation as well as other risky activities, when they have to decide whether to start and continue their activities, they should receive the correct incentives not to neglect risk and information acquisition. Under scientific uncertainty, the 'precautionary principle' should lead to such behaviours, but it remains difficult to apply. In this regard, this section proposes to analyze how, at the innovator level, through the existing regulatory framework of risk prevention, in particular strict liability rule and negligence rule, we may find a way to implement such a principle by developing incentives to both enhance innovation and information acquisition.

4.1 The strict liability rule

Under a strict liability rule, the innovator is fully liable and thus he must pay for the damages caused by his activities. Nevertheless, his responsibility is engaged only if the victims can demonstrate a causality link between the damage and the activity or the product sold. Such a rule implies that the innovator needs to consider the effect on accident losses of both his level of care, and his level of activity. Thus, he exercises optimal prevention efforts to reduce the risks and undertakes the optimal level of care (i.e. paying the optimal cost of care).

In our model, we investigate intertemporal investment behaviour in a potentially risky project. We suppose that if an accident happens, the innovator suffers the financial cost. Thus, we implicitly suppose that the innovator is constrained by a strict liability rule. Moreover, we define the level of care as the level of investment in research (i.e. information acquisition). By investing in research, the innovator gets information on the dangerousness of his activity and then he can decide to stop it or not. It is a way to underline the impact of the liability rule on the innovator behaviour, although both the ex-ante investment I and the cost of damages K which do not depend on C (like in the case in the usual models of liability). Indeed, if the innovator exercises the level of care C and receives a signal of high danger (i.e. $\sigma = h$), he stops his activity and then limits the cost of damages (i.e. $K' < K$). Otherwise, if he does not exercise C, he never stops his project

[5] $\widehat{\theta}(\beta) = \widehat{\theta}(1)$ and $\overline{\beta} = \overline{\overline{\beta}}$.

and therefore he exposes the environment or the people health to a more severe risk, for which he is responsible. In such a case, he suffers a higher financial cost in case of accident.

A liability rule is efficient when it gives the right incentives to prevent risks and to reduce damages. In our model, the efficiency of the strict liability rule is linked to the innovator's ability to obtain information that may reduce at the end the financial cost of damages. In other words, the rule is efficient when the innovator invests in research and gets useful information. Moreover, when the agent's selves can perfectly internalize the externality they exert on future selves (i.e. $\beta = 1$), strict liability rule leads the innovator to undertake the optimal *'cost of care'*(Shavell 1980, 1992, Miceli, 1997). Thus, we say that the rule is fully efficient when the innovator is willing to pay this optimal cost of care $C^*(1)$. Otherwise, if the investment in research is lower, the rule is less efficient, and if the investment is null, the rule is not efficient. We define the efficiency of a strict liability rule like the ability of an innovator to invest in research. We obtain

Result 3 *The impact of time inconsistency is such that for $\beta \in [0, \overline{\beta}]$, the strict liability rule is inefficient; for $\beta \in]\overline{\beta}, 1[$, the strict liability rule efficiency is increasing with β; for $\beta = 1$, the strict liability rule is fully efficient.*

Time inconsistency leads to a lower and decreasing investment in research. Moreover, for small values of β, innovators might prefer being liable and develop their activities, than getting information on the risk of damage of their project and being tempted to stop it prematurely. Thus, hyperbolic discounting preferences limits the efficiency of the strict liability rule to incite the innovator to acquire information.

4.2 The negligence rule

Under a negligence rule, it is said that *"the injurer* [innovator] *is liable for the victim's only if he failed to take a minimum level of care"* (Miceli, 1997), also defined as a *'due standard of care'* by Shavell (1980, 1992). In such a case, he has to pay for the damages. On the other hand, if he exercises at least the level of care, he is not liable and the victims or the State pay the financial cost.

In our model, we define by $C^{NR}(\beta)$ the level of investment in research to exercise, not to be liable if an accident occurs. Since $C^{NR}(\beta)$ is an investment in information on the probability of damage to reduce the uncertainty linked to the project, it does not represent the ability of the innovator to exercise physical prevention efforts. Thus, we define $C^{NR}(\beta)$ like a *due standard of research.*[6]

[6]We define $C^{NR}(\beta)$ like a due standard of research and not a due standard of care, because it is an

According to the literature, we should define $C^{NR}(\beta)$ as the optimal cost of investment in research, from which the innovator is not liable for the damage. However, due to time inconsistency and uncertainty, for low β (i.e. $\beta \in [0, \overline{\beta}]$), the optimal level of investment in research is null. Thus, if $C^{NR}(\beta) = C^*(\beta) = 0$ for $\beta \in [0, \underline{\beta}]$, the innovator will never be liable when an accident occurs. Applying a negligence rule would have no impact on the innovator's behaviour, except if we define, for low level of β, $C^{NR}(\beta)$ as the imposed level of investment in research, in order to force the innovator to acquire information (i.e. to exercise a minimum level of care), whatever his intertemporal preferences, and to behave according to this information.

Nevertheless, to make the investor change his behaviour, it should also be on his interest to undertake such imposed investment. Thus, for $\beta \in]0, \overline{\beta}]$, his intertemporal expected payoff needs to be higher when he is not liable than when he is. In such a case, he is then never tempted to invest less than $C^{NR}(\beta)$ and then to be at fault. Remember that according to Proposition 1, at period 1, the investor has to choose between two strategies: to carry on his project whatever the signal he receives, or to continue (to stop) it only if he gets signal l (h). We define p_σ as the probability to receive the signal σ:

$$p_l(C) = p_0(1 - f(C)) + (1 - p_0)f(C) \text{ and } p_h(C) = p_0 f(C) + (1 - p_0)(1 - f(C)).$$

Thus, at period 0, if the agent undertakes the due standard of research, his expected intertemporal payoffs according to the strategies chosen are

$$\begin{aligned} V_0^{NR}(1, 1, C) &= V_0(1, 1, C) \mid_{K=K'=0} = -I - C + \beta R_2, \\ V_0^{NR}(0, 1, C) &= V_0(0, 1, C) \mid_{K=K'=0} = -I - C + \beta p_l R_2 + \beta p_h D \end{aligned}$$

Since we define $C^{NR}(\beta)$ as the minimum investment in research that makes him change his behaviour: $C^{NR}(\beta)$ is thus the minimum cost of research that provides him information that influence, when he is not liable, his decision to stop or continue the project at period 1. In others words, $C^{NR}(\beta)$ is such that the innovator is at least indifferent between getting $V_0^{NR}(1, 1, C)$ or $V_0^{NR}(0, 1, C)$. Moreover, we know that for low value of β, the agent is more concerned by present satisfaction, he optimally prefers not investing in information and getting V_0^{NL}. To avoid such effect, $C^{NR}(\beta)$ has also to be the cost that leads the innovator to be indifferent between *"being informed but not liable"*, and *"staying uniformed but being liable for damages"*. In others words, if he refuses to pay this due standard of research, he pays the financial cost of damages, if an accident occurs, and he gets self-0's expected payoff, when self-0 decides not to obtain information, i.e. V_0^{NL}. Otherwise, if he invests $C^{NR}(\beta)$, he does not have to pay for damages, but the

information acquisition on the risk of damage and not in physical prevention measures. Nevertheless, in a general approach, they are equivalent notions.

information is useful to limit the cost of these damages (i.e. even if the innovator does not pay for damages, if he receives a signal of high danger ($\sigma = h$), he stops his activity).

Therefore, for low level of β, the due standard of research is such that

$$V_0^{NR}(1,1,C) = V_0^{NR}(0,1,C) \text{ and } V_0^{NR}(0,1,C) = V_0^{NL}(\beta).$$

$$\text{which is equivalent to } C^{NR}(\beta) = \beta E(\theta)K \tag{4}$$

Thus, if the investors invests less than $C^{NR}(\beta)$, he is liable for damages and gets a lower payoff, than the one he could obtain if he invests at least $C^{NR}(\beta)$. Moreover, he also obtains useful information and then limits people and environment's exposition to the dangerousness of his activity.

On figure 4 below, we represent, for a given $\beta \in [0, \overline{\beta}]$, $C^{NR}(\beta)$, as well as the investor expected payoff whereas he respects or not the due standard of research (black line). For low value of β, we also could have imposed $C^{NR}(\beta)) = C_{01}^*(\beta) \mid_{K=K'=0}$ as the due standard of research. Indeed, as we force the investor to change his behaviour and to choose the strategy $[x_l^* = 1,\ x_h^* = 0]$, he should then prefer investing $C_{01}(\beta) \mid_{K=K'=0}$ in information, which allows him to maximize his expected payoff $V_0^{NR}(0,1,C)$, and always provides him a higher payoff than the one he gets without any information if he is liable for damages ($V_0^{NL}(\beta)$). Thus for $\beta \in [0, \overline{\beta}]$, the due standard of research defined by (4) is the smallest value of the due standard of research to impose.

Otherwise, for $\beta \in]\overline{\beta}, 1]$, under a strict liability rule, the innovator optimally invests $C_{01}(\beta)$ to obtain information . Thus, the due standard of research under negligence should be equal to the optimal level research $C_{01}^*(\beta)$, when the investor is not liable (i.e. $K = K' = 0$).

Overall, we obtain:

Proposition 6 *The due standard of research* $C^{NR}(\beta)$ *is such that for* $\beta \in [0, \overline{\beta}[$, $C^{NR}(\beta) \in [\underline{C}^{NR}(\beta), C_{01}^*(\beta) \mid_{K=K'=0}]$, *with* $\underline{C}^{NR}(\beta) = \beta E(\theta)K$ *; for* $\beta \in [\overline{\beta}, 1]$, $C^{NR}(\beta) = C_{01}^*(\beta) \mid_{K=K'=0}$.

We remark that for all β, $C^{NR}(\beta)$ is strictly positive. In term of information acquisition, the negligence rule is thus more efficient than the strict liability rule; it leads to an investment in research under time inconsistency closer to the one exercised under time consistency.

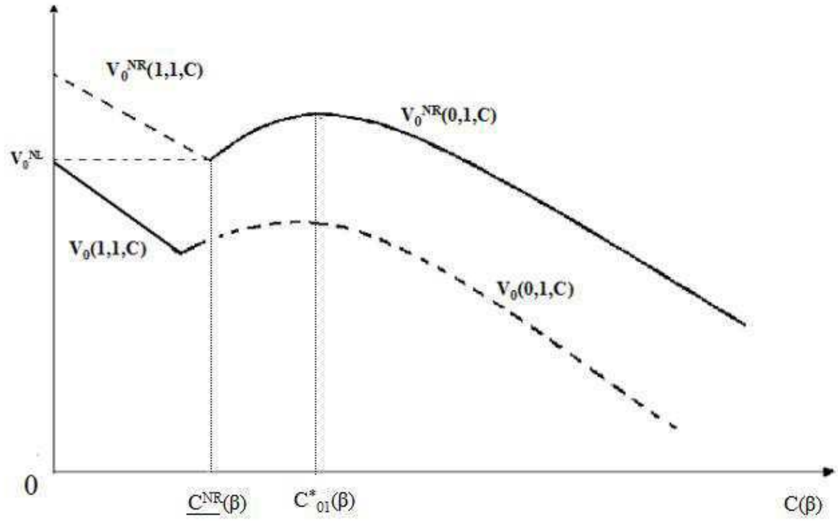

Figure 4: Due standard of research.

Furthermore, a negligence rule may limit innovation. An informed innovator has more opportunities to stop his project. In particular, for low β, while a negligence rule lays down a minimum investment in research, a strict liability rule leads the innovator to be uniformed and always to continue the project. We then obtain the following result

Result 4 *Comparing the impact of strict liability rule and negligence rule on innovation and information acquisition, we obtain for* $\beta \in [0, \overline{\beta}[$*, a negligence rule favours information acquisition but limits innovation, while a strict liability rule favours innovation but limits information acquisition; For* $\beta \in [\overline{\beta}, 1]$*, both rules are equivalent and they allow to a combination between innovation and information acquisition.*

However, from a social perspective, the negligence rule is more efficient. It proposes a minimum research investment that a hyperbolic investor is willing to undertake, and provides information that may influence the innovator's decision to continue or not his project. Thus ,it allows to limit damages in case of an accident happens. Hence, we obtain the following result:

Result 5 *Under hyperbolic discounting preferences and uncertainty, the negligence rule is socially more efficient than the strict liability rule.*

Nevertheless, under hyperbolic discounting preferences and uncertainty, both liability rules are difficult to apply and can have pervert effect on innovation and information acquisition: combining both of them remain difficult.

5 Conclusion

In this paper, we study the information acquisition of an agent with hyperbolic discounting preferences who wants to undertake a potential dangerous activities. Possible examples of application of this model include innovators in new technologies (e.g. nanotechnologies, mobile phones), pharmaceutical firms (e.g. development and production of new drugs) or chemical firms (e.g. production of new fertilizers). Since for the GMOs plants farm's example, in all those cases innovators produce while they may have an incomplete knowledge on the dangerousness of their activities in the long run. We find that for large enough values of the discount rate, the innovator acquires information on the damages risks. His investment in research is increasing with the value of β: it tends towards the level of investment reached when the agent has time consistent preferences and is allowed to commit in the long run. On the other hand, for small values of the discount rate the innovator may ignore the information: he refuses to invest in research to obtain information on the dangerousness of his activity in order to achieve his project. Moreover, if the hyperbolic discounting preferences limit the innovator's ability to acquire information, the lack of self-control (i.e. no commitment between the different future selves of the innovators) strengthens this limitation.

We also observe that if the investor does not have the possibility to recover a part of his initial investment when he gives up his project (i.e. no salvage value (D)), or if he can only obtain this salvage value at the project's date of maturity (i.e. at the period 2), both the discounting and the self-control effects would not have any impact on his decisions to completely or partially achieve his project. Actually, the innovator with time inconsistency preferences is more concerned by current rewards than by future ones and in particular when there is a possible delayed cost. Since D is given at period 1, the hyperbolic innovator is more likely than the exponential one to earn D now and to stop his project, than to wait for future gains and maybe to suffer the delayed cost of damages.

Moreover, we underline that hyperbolic discounting preferences also limit the efficiency of the legal framework, and in particular of the strict liability rule. If there are situations in which an innovator prefers being uninformed in order to develop his activity, one should define others rules and incentives to ensure that investments in innovation's projects are not done to the detriment of information acquisition and conversely. In this regard, even if it does not always lead to an optimal choice, we consider the application of a complete negligence rule as a possible alternative solution.

However, lessons have to be learned from practical examples. Regarding GMO crops and sales, the current legislation does not seem to be completely efficient to prevent potential risks, to ensure a safe use of such organisms and to identify who should take responsibility for them. For example, it is particularly the case when non-modified organisms are contaminated by modified organisms through pollens scattering. This confirms our results: if scientific uncertainty limits the effect of a strict liability on producers' decisions, time inconsistent preferences strengthen such limitation. Nevertheless, experiences also underline the persuasive role that strict liability can play on producers behaviour, even if its application remains difficult. Weill (2005) notes that when the 'burden of the proof' is in on the potential injurer, and not on the victims, as it is the case under a negligence rule, producers are more likely to stop potentially dangerous products from the market. The recent European legislation on chemicals (REACH directive)[7] tackles the challenging issue related to the application of the precautionary principle to both enhance innovation as well as people and environment protection. It is based on a strict liability rule, under which the 'burden of the proof' is on the industry, but it also requires manufacturers and importers to take the responsibility "to gather information on the properties and risks of all substances produced or imported".[8] This legislation proposes an interesting way to implement the precautionary principle to deal with chemicals, by combining the positive effects of a strict liability rule, to a research obligation for firms that should avoid the negative ones. This approach should provide relevant elements in the current debate on the regulation of others kind of scientific and/or technological innovation.

Appendix

Proof of Proposition 1

At period 1, the innovator receives the signal $\sigma \in \{h, l\}$. For all $C \geq 0$, he chooses to continue i.e. $x_\sigma = 1$ if

$$V_1(1, \sigma, C) \geq V_1(0, \sigma, C) \quad \text{i.e.} \quad E(\theta|\sigma, C) \leq \widehat{\theta}(\beta) \equiv \frac{\beta R_2 - D}{\beta(K - K')}.$$

[7]REACH stands for Registration, Evaluation, Authorization and Restriction of Chemicals
[8]for more details on REACH, see European Commission [28].

■

Proof of Lemma 1

Since $\theta^H > \theta^L$ and for all $C \geq 0$, $f(C) \geq \frac{1}{2}$ we obtain that

$$E(\theta|l, C) - E(\theta) = \frac{(1-p_0)p_0(\theta^H - \theta^L)(1 - 2f(C))}{(1-p_0)f(C) + p_0(1 - f(C))} \leq 0$$

and

$$E(\theta) - E(\theta|h, C) = \frac{(1-p_0)p_0(\theta^L - \theta^H)(2f(C) - 1)}{p_0 f(C) + (1-p_0)(1 - f(C))} \leq 0.$$

Thus, $E(\theta|l, C) \leq E(\theta) \leq E(\theta|h, C)$.

We differentiate $E(\theta|h, C)$ with respect to C, we obtain

$$\frac{(1-p_0)p_0 f'(C)(\theta^H - \theta^L)}{[(1-p_0)(1 - f(C)) + p_0 f(C)]^2}$$

which is positive. Thus, $E(\theta|h, C)$ is increasing with C.

We differentiate $E(\theta|l, C)$ with respect to C, we obtain

$$\frac{(1-p_0)p_0 f'(C)((\theta^L - \theta^H)}{[p_0(1 - f(C)) + (1-p_0)f(C)]^2}$$

which is negative. Thus, $E(\theta|l, C)$ is decreasing with C.

■

Proof of Proposition 2

Concavity of $V_0(0, 1, C)$: We differentiate $V_0(0, 1, C)$ with respect to C, we obtain

$$-1 + \beta[(1-p_0)B^L - p_0 B^H]f'(C). \tag{5}$$

We differentiate equation (5) with respect to C, we obtain

$$\beta[(1-p_0)B^L - p_0 B^H]f''(C).$$

Since f is concave, B^L is positive and B^H is negative then $V_0(0, 1, C)$ is concave.

The solution $C_{01}(\beta)$ to problem (2) is characterized by

$$-1+\beta[(1-p_0)B^L-p_0B^H]f'(C_{01}(\beta))=0 \Leftrightarrow f'(C_{01}(\beta))=\frac{1}{\beta[(1-p_0)B^L-p_0B^H]}.$$

Since B^L is positive and B^H is negative, we verify that $f'(C_{01}(\beta))>0$.

We easily check that $f'(C_{01}(.))$ is decreasing with β. Since f is concave then C_{01} is increasing with β.

■

Proof of Proposition 3

According to Lemma 1 and condition (1), $\widehat{C}(\beta)$ the smallest $C\geq 0$ which satisfies

$$E(\theta|l,C)\leq\widehat{\theta}(\beta)\leq E(\theta|h,C)$$

is such that either

$$E(\theta|l,\widehat{C}(\beta))=\widehat{\theta}(\beta)<E(\theta|h,\widehat{C}(\beta)) \text{ or } E(\theta|l,\widehat{C}(\beta))<\widehat{\theta}(\beta)=E(\theta|h,\widehat{C}(\beta))$$

Define $\widehat{C}_1(\beta)$ which verifies that $E(\theta|l,\widehat{C}(\beta))=\widehat{\theta}(\beta)$ we obtain

$$f(\widehat{C}_1(\beta))=\frac{p_0(\theta^H-\widehat{\theta}(\beta))}{p_0(\theta^H-\widehat{\theta}(\beta))+(1-p_0)(\widehat{\theta}(\beta)-\theta^L)}.$$

Define $\widehat{C}_2(\beta)$ which verifies that $E(\theta|h,\widehat{C}(\beta))=\widehat{\theta}(\beta)$ we obtain

$$f(\widehat{C}_2(\beta))=\frac{(1-p_0)(\widehat{\theta}(\beta)-\theta^L)}{p_0(\theta^H-\widehat{\theta}(\beta))+(1-p_0)(\widehat{\theta}(\beta)-\theta^L)}.$$

Since f is increasing to compare $\widehat{C}_1(\beta)$ and $\widehat{C}_2(\beta)$ we compare $f(\widehat{C}_1(\beta))$ and $f(\widehat{C}_2(\beta))$. We obtain that if $E(\theta)<\widehat{\theta}(\beta)$ then $\widehat{C}(\beta)=\widehat{C}_1(\beta)$; and if $E(\theta)>\widehat{\theta}(\beta)$ then $\widehat{C}(\beta)=\widehat{C}_2(\beta)$.

According to condition (1), we obtain that $\widehat{C}(\beta)=\widehat{C}_1(\beta)$. Moreover, we easily show that

$$f(\widehat{C}(\beta))\geq\frac{1}{2}.$$

We differentiate $f(\widehat{C}(\beta))$ with respect to β we obtain

$$\frac{-p_0(1-p_0)\widehat{\theta}'(\beta)(\theta^H-\theta^L)}{[p_0(\theta^H-\widehat{\theta}(\beta))+(1-p_0)(\widehat{\theta}(\beta)-\theta^L)]^2}$$

that is negative. According to Lemma 1 and condition (1), since f is increasing then $\widehat{C}(\beta)$ is decreasing with β.

■

Proof of Proposition 4

Since $\widehat{C}(\beta)$ is decreasing with β and C_{01} is increasing with β there exists a $\overline{\beta}\in]0,1]$ such that $C_{01}(\overline{\beta})=\widehat{C}(\overline{\beta})$.

Since $\widehat{C}(\beta)$ is the smallest $C\geq 0$ which satisfies the following condition

$$E(\theta|l,C)\leq\widehat{\theta}(\beta)\leq E(\theta|h,C),$$

we get that if $\beta\in[0,\overline{\beta}]$ then $C^*_{01}(\beta)=\widehat{C}(\beta)$; and if $\beta\in]\overline{\beta},1]$ then $C^*_{01}(\beta)=C_{01}(\beta)$.

■

Proof of Proposition 5

The optimal research investment $C^*(\beta)$ is such that

- if $V_0(0,1,C^*_{01}(\beta))>V_0(1,1,0)$ then $C^*(\beta)=C^*_{01}(\beta)$;
- otherwise $C^*(\beta)=0$.

We compare $V_0(0,1,C^*_{01}(\beta))$ and $V_0(1,1,0)$. According to Proposition 4, we have for all $\beta\in[0,\overline{\beta}]$ then $C^*_{01}(\beta)=\widehat{C}(\beta)$; for all $\beta\in]\overline{\beta},1]$ then $C^*_{01}(\beta)=C_{01}(\beta)$.

We first compare $V_0(0,1,\widehat{C}(\beta))$ and $V_0(1,1,0)$. We obtain

$$V_0(0,1,\widehat{C}(\beta))-V_0(1,1,0)=-\widehat{C}(\beta)+\beta[-p_0f(\widehat{C}(\beta))B^H-(1-p_0)(1-f(\widehat{C}(\beta)))B^L].$$

We replace $f(\widehat{C}(\beta))$. We obtain

$$-\widehat{C}(\beta)+\beta\left[\frac{p_0^2(\theta^H-\widehat{\theta}(\beta))B^H-(1-p_0)^2(\widehat{\theta}(\beta)-\theta^L)B^L}{p_0(\theta^H-\widehat{\theta}(\beta))+(1-p_0)(\widehat{\theta}(\beta)-\theta^L)}\right]$$

which is negative because of condition (1). Thus for all $\beta\in[0,\overline{\beta}]$ we obtain that

$$V_0(0,1,\widehat{C}(\beta)))<V_0(1,1,0).$$

Then $C^*(\beta)=0$.

Now we compare $V_0(0,1,C_{01}(\beta))$ and $V_0(1,1,0)$. It is easily verified that $V_0(1,1,0)$ and $V_0(0,1,C)$ are both increasing with β. We differentiate $V_0(1,1,0)$ with respect to β we obtain

$$p_0(R_2-\theta^HK)+(1-p_0)(R_2-\theta^LK)$$

that is positive by assumption.

We differentiate $V_0(0,1,C)$ with respect to β we obtain

$$\begin{array}{l} p_0(1-f(C))(R_2-\theta^H K)+(1-p_0)f(C)(R_2-\theta^L K) \\ +p_0 f(C)(D-\theta^H K')+(1-p_0)(1-f(C))(D-\theta^L K') \end{array}$$

which is positive by assumption.

We suppose that $V_0(0,1,C_{01}(\beta))=V_0(1,1,0)$ this implies that

$$f(C_{01}(\beta))=\frac{\beta(1-p_0)B^L+C_{01}(\beta)}{\beta[(1-p_0)B^L-p_0B^H]}. \tag{6}$$

We differentiate $V_0(0,1,C_{01}(\beta))$ and $V_0(1,1,0)$ with respect to β and we replace $f(C_{01})$ by the right hand side of equation (6). Since for all $\beta\in[0,1]$ $C_{01}(\beta)\geq 0$, we obtain that

$$\frac{\partial V_0(0,1,C_{01}(\beta)}{\partial\beta})\geq\frac{\partial V_0(1,1,0)}{\partial\beta}.$$

Thus, there exists $\widetilde{\beta}\in[0,1]$ such that $V_0(0,1,C_{01}(\widetilde{\beta}))=V_0(1,1,0)$ and

- for all $\beta\in[0,\widetilde{\beta}]$ then $V_0(0,1,C_{01}(\beta))\leq V_0(1,1,0)$;
- for all $\beta\in]\widetilde{\beta},1]$ then $V_0(0,1,C_{01}(\beta))>V_0(1,1,0)$.

We notice that for $\beta=0$, we obtain $C_{01}(0)=0$ and then $V_0(0,1,C_{01}(0))=V_0(1,1,0)=-I$. Thus, $\widetilde{\beta}=0$ and for all for all $\beta\in]0,1]$ then $V_0(0,1,C_{01}(\beta))>V_0(1,1,0)$. Since $\beta\neq 0$ then for all for all $\beta\in]\overline{\beta},1]$ $C^*(\beta)=C_{01}(\beta)$.

Overall we obtain for all $\beta\in[0,\overline{\beta}]$ then $C^*(\beta)=0$; for all $\beta\in]\overline{\beta},1]$ then $C^*(\beta)=C_{01}(\beta)$.

■

Proof of Lemma 2

Similar to the proof of Proposition 1, thus omitted.

■

Proof of Lemma 3

Similar to the proof of Proposition 5, thus omitted.

■

Proof of Lemma 4

By definition

$$C_{01}(\overline{\beta}) = \widehat{C}(\overline{\beta}) \text{ and } C_{01}(\overline{\overline{\beta}}) = \widehat{C}(1).$$

Since $\widehat{C}$ is decreasing with β then

$$\widehat{C}(1) < \widehat{C}(\bar{\beta}) \text{ and so } C_{01}(\overline{\overline{\beta}}) < C_{01}(\overline{\beta}).$$

Since C_{01} is increasing with β we obtain

$$\overline{\overline{\beta}} < \overline{\beta}.$$

■

Proof of Proposition 6

For $\beta \in [0, \overline{\beta}]$, $\underline{C}^{NR}(\beta)$ is characterized by

$$V_0^{NR}(1,1,C) = V_0^{NR}(0,1,\underline{C}^{NR}) \text{ i.e. } \beta R_2(1 - p_l(\underline{C}^{NR}(\beta))) - \beta p_h(\underline{C}^{NR}(\beta))D = 0$$

and

$$V_0^{NR}(0,1,\underline{C}^{NR}(\beta)) = V_0^{NL} \text{ i.e. } \underline{C}^{NR}(\beta) + \beta p_h(\underline{C}^{NR}(\beta))(R_2 - D) = \beta E(\theta)K.$$

Thus, we get $\underline{C}^{NR}(\beta) = \beta E(\theta)K$.

However, if the agent invests $\underline{C}^{NR}(\beta)$, his intertemporal pay-off is $V_0^{NR}(0,1,C)$, and he solves the following maximisation problem:

$$\begin{cases} \max_C V_0^{NR}(0,1,C) \\ E(\theta|l,C) < \widehat{\theta}(\beta) < E(\theta|h,C). \end{cases}$$

that is equivalent to

$$\begin{cases} \max_C V_0(0,1,C)_{|K=0,K'=0} \\ E(\theta|l,C) < \widehat{\theta}(\beta) < E(\theta|h,C). \end{cases}$$

So we obtain: $C^{NR}(\beta) = C^*_{01}(\beta) \mid_{K=K'=0}$.

Thus, for all $\beta \in [0, \overline{\beta}]$, $C^{NR}(\beta) \in [\underline{C}^{NR}(\beta), C^*_{01}(\beta) \mid_{K=K'=0}]$, with $\underline{C}^{NR}(\beta) = \beta E(\theta)K$.

Since for $\beta \in]\overline{\beta}, 1]$ it is optimal to invest in research. The innovator solves the following problem

$$\begin{cases} \max_C V_0^{NR}(0, 1, C) \\ E(\theta|l, C) < \widehat{\theta}(\beta) < E(\theta|h, C). \end{cases}$$

Thus, we obtain that $C^{NR}(\beta) = C_{01}^*(\beta) \mid_{K=K'=0}$.

Overall we obtain that $\forall \beta \in [0, \overline{\beta}[$, $C^{NR}(\beta) \in [\underline{C}^{NR}(\beta), C_{01}^*(\beta) \mid_{K=K'=0}]$; et $\forall \beta \in [\overline{\beta}, 1]$, $C^{NR}(\beta) = C_{01}^*(\beta) \mid_{K=K'=0}$.

■

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